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JUNE, 1956

OTTAWA
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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
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PRESIDENTIAL ADDRESS

The Magmatic vs Metamorphic Source of Ores

J. E. HAWLEY, F.R.S.C.

ABSTRACT

Magmatic and metamorphic processes by which ores may be concentrated are reviewed; this review is followed by a re-examination of some Precambrian epigenetic deposits in the Superior and Grenville subprovinces of eastern Canada. Magmatic processes are considered much the more efficient and probable and best explain textures and occurrence of gold, copper-zinc, and nickel-copper ores of the Superior subprovince, and high temperature zinc deposits of the Grenville. Minor contamination of these by isotopes of lead and certain trace metals or gangue constituents may be attributed to indistinguishable metamorphic *processes* or *products*. Proof that metamorphic processes are effective in mobilizing disseminated metals is rare or lacking, but is granted for the redistribution of previously formed deposits. Re-study of scattered molybdenite and larger magnetite deposits in the Grenville to establish their relation to granitization is suggested. Minor galena-calcite veins here appear related to the regenerated Alpine type.

AS a topic for discussion at this meeting of the Royal Society I have chosen a current problem of the genesis of ores. In particular I should like to consider the question of source—magmatic or metamorphic, or both —of some of our Canadian Precambrian epigenetic deposits of the types usually classed as magmatic sulphide or hydrothermal.

Throughout recent literature you will find hints, innuendoes, and even outright suggestions by plutonists, some of whom hold that granitic magmas are but a figment of the imagination or, at best, of little consequence, and that such ores, even in highly metamorphic terranes, are metamorphic in origin. To a magmatist and to many economic geologists, this is rank heresy. Even the term "hydrothermal" seems to be falling into disrepute. My purpose, then, is to focus the attention particularly of economic geologists on the many puzzling and at times baffling questions being raised, and to suggest that we take a new look at many Canadian occurrences and avoid taking too much for granted. In approaching the problem, may I assure you, I have tried to avoid prejudice as far as possible—though remaining a confirmed magmatist who is willing to admit granitization as a fact.

This is much too large a subject to review in great detail. There is time only to consider, first, the various mechanisms which have been suggested as factors in the concentration, transportation, and deposition of ore materials, under the two headings, magmatic and metamorphic; and, second,

to examine a few of our deposits, whether or not they have been considered heretofore as stemming from some other source than magmas.

The problem is clearly related to the very existence of magmas and to the concepts of processes involved in granitization. It thus calls for a re-examination of ideas on the nature of ore fluids and their behaviour, and the fate of disseminated metals in common rocks during metamorphism of varying intensities. It is also intimately intertwined with the problem of the number and dates of Precambrian orogenies.

Many ore deposits in eastern Canada afford an excellent opportunity for the study and consideration of such problems. There, in the Superior and Grenville provinces, we have two contrasting types of Precambrian metamorphic terrane. In the one, the Superior province, are remnants of synclinal troughs of sediments and volcanics which have attained the green schist and locally even higher grades of metamorphism; abundant granitic to granodioritic intrusions; and undoubtedly granitized rocks occupying much of the large areas indicated on our maps simply as granite. In the other, the Grenville area to the south, is exposed a higher rank metamorphism where granitic gneisses, granites, and "granites" predominate, and where quartzites, argillites, and limestones have clearly been granitized to varying degrees.

Texts on ore deposits, in contrast to those now available on petrogenic theory, give little attention to this whole problem. While it is perhaps only right that students of ore deposits should look to petrologists for ideas, it would seem that economic geologists are still waiting for a decision as to just how many igneous-looking rocks are the products of crystallization of magmas and how many are metamorphic or plutonic. Some firm agreement as to the relative importance of the various processes envisaged as occurring during metamorphism would also be helpful. We cannot but be grateful, however, for the stimulation these new views are giving to all geologists. Certainly students of ore deposits can and should contribute to the growing discussion. If granites may be formed by both magmatic and metamorphic processes, why not ores?

Magmas and Ores

The classical concept of the genetic relation of magmas and many epigenetic ore deposits is too well known to require much review here. At least for many of our Precambrian metalliferous areas, most Canadian geologists would probably agree that the associated rocks of igneous aspect—basic, intermediate, and granitic—have a magmatic origin: that is, that they have been intruded as liquids and crystallized. For our purpose we need not try to distinguish between what may be termed *primary* magmas arising from a gabbroic or even a peridotite layer; magmas which may form by differentiation and/or assimilation; and *secondary* or "neo-magmas" formed by the remelting or differential fusion (anatexis) of deeply buried rocks, and the squeezing out of such fluids, whatever they may be called. Once formed,

these liquids may later cool, obey the laws of crystallization, and give up whatever ore fluids they contain. One would not deny, however, that these different modes of origin would not seriously affect the ore content. In fact they do, from the magmatic view, explain readily, though perhaps only in part, the variations in ores in the same, as well as in different, metallogenic provinces.

The efficiency of the multiple processes by which ore constituents are considered to be concentrated from magmas, apparently overlooked or summarily dismissed by plutonists, seems well founded both on theoretical grounds and on actual observations of such undisputed magmatic rocks as layered intrusives. These processes include crystallization–differentiation, liquation or partial miscibility (as between sulphides and silicates), and concentration in residual liquids of substances that do not enter earlier formed oxides and silicates, from which stem the hydrothermal solutions. Neumann (1948) has given an excellent theoretical demonstration of how metals may be segregated in a crystallizing magma and partitioned between growing crystals, a molten phase (magma), and a fluid (hydrothermal) phase, according to their solubility. This *endo-magmatic* differentiation, combined with changes in temperature and pressure, etc., affecting such fluids in their subsequent (exo-magmatic) history affords a logical explanation for the normal paragenesis of primary magmatic ores and the evolution of a series of fluids which appear to supply successive additions of metals to ore deposits.

A refinement of Neumann's work with Mead and Vitaliano (1954) considers the effects of conditions of crystallization, isomorphous series, resorption, and changes in temperature and pressure. Theoretical curves receive confirmation from studies by Wagar and Mitchell (1951) on the Skaergaard complex in which the distribution of cobalt, nickel, and other metals in various crops of crystals was indicated.

Solid solubility of ions in the crystals of a magma, and of course in any growing crystals (metamorphic or others), is also dependent on various diadochial factors which assist or hinder their entrance and bonding in crystal edifices. Goldschmidt (1937, 1944, 1954) and many others have shown the importance of ionic radii, ionic charge, ionic potential, and type of chemical bonding. Ringwood (1955) shows in considerable detail the importance of the electro-negativity of such ions, as it affects the type and strength of bonding. He draws on contributions made by glass chemists and distinguishes between ions which enter holes in silicate networks, those forming complexes, and an intermediate group that maintains an equilibrium between the two. While such factors have been applied chiefly to magmas and clearly show the tendency of many metals to concentrate in residual liquids, they are also applicable to metamorphic processes of recrystallization and reactions at temperatures and pressures of somewhat lower intensity than prevail in magmas.

There has been much argument as to the nature of magmatic ore-forming

fluids, whether gaseous or liquid, dilute or concentrated, acid or alkaline, and we need not labour these points, but note the bearing that studies on the synthesis of ore minerals have on this subject, studies emphasizing the possible role of acid, alkaline, alkaline sulphide liquids, neutralized chloride ions, as well as colloids. Changes in composition by reaction with wall rocks, and acquisition of certain constituents from these, are clearly recognized as possible during the ascent of ore fluids from depth, but it is not easy to distinguish original from acquired constituents, and the uniformity of many deposits over thousands of feet of depth is, in many cases, very striking.

In the transport of ore constituents of magmatic origin, emphasis has been put on the flow of such fluids from areas of higher to those of lower temperature and pressure, but ionic diffusion through such fluids as well as through solids has been recognized to be as important a process here as it is in metamorphic reactions, especially in the formation of replacement ore bodies and wall rock alteration.

It is in the deposition of such ores that we come to a striking characteristic, the *normal paragenesis*; especially interesting is its non-repetitive character, which obtains, with minor variations, in so many ores, whether copper, lead-zinc, or gold. Again we find much debate on this subject as to whether the paragenesis represents the order of deposition of minerals from a single liquid or from a succession of ore fluids of varying composition. Both views are undoubtedly true to some extent, but the balance of evidence in most deposits favours the latter, as shown both by replacement phenomena of one ore mineral by another and by the structural control and spatial distribution of "late" minerals with respect to "early." A logical explanation for the normal paragenesis has been offered by Newhouse (1928) and Neumann (1948) on the basis of a "primary" magmatic derivation, and in fact such a paragenesis is accepted by many as a safe criterion for an origin of this type. (Schneiderhöhn, 1954, translation by J. S. Brown.)

Here, too, we should recall the abundant evidence, direct and indirect, for both the thermal and the hydrous character of such fluids, no matter what their source: aqueous inclusions in quartz and other minerals, the association of hydrous silicates, the introduction of both ore and gangue minerals, and the removal of vast quantities of host-rock minerals during the formation of replacement ores.

The relations of most ore deposits such as these to intrusive rocks with which they are spatially associated—with the possible exception of some disseminated sulphides in basic rocks—almost invariably indicate their younger age: that is, intrusion of such magmas, solidification, fracturing, and ore deposition form the usual sequence. Such ore fluids are, therefore, assumed to arise at depth from the still crystallizing portion of the parent magma of one or other of the associated intrusive rocks, some of which may be siliceous, some basic. In the majority of cases there is no indication of further orogenic events or metamorphism except for a continuation of fracturing and faulting. It is thus at least as logical to assume the existence

of a more deeply seated parent magma as it is to assume that the underlying rocks are still undergoing progressive metamorphism (in the absence of magmas) and supplying ore fluids at such a time.

Metamorphism and Ores

In discussing the role of metamorphism in the formation of ores we may well follow Read (1948) in accepting Daly's (1917) definition of metamorphism as "the sum of the processes which, working below the shell of weathering, cause the recrystallization of the original crystallized materials in rocks, with or without chemical reactions, or the crystallization of original amorphous materials in rocks, the change in each case not being accompanied by general melting of the rock or by any general simultaneous solution of its constituents." As noted above we may exclude here such processes as give rise to "neo-magmas" which are not too readily distinguished from any others.

In general the processes are the result of heat and pressure driving rock (and other) minerals towards equilibrium with a new environment. Although metamorphic petrologists may not yet agree as to their relative importance in producing various plutonic and metamorphic rock types, let alone ores, the processes include local melting, recrystallization (usually a purification process), ionic diffusion in the solid or dry state (according to the French school) or diffusion with the aid of water and possibly other volatiles, and the expression of such liquids during orogenic and even epeirogenic movements. Ore constituents are conceived of as being mobilized by these processes either from a highly disseminated state in rock minerals of the basement or from a more concentrated state, such as previously formed ore deposits as advocated by Schneiderhöhn (1954). The constituents are then driven upward, from the deep-seated plutonic assemblages of granites, migmatites, and gneisses, at the very roots of folded mountains, to the transitional zone of regionally metamorphosed schists, or to even higher levels (the cover rocks), as has been shown, for example, with Ca, Na, Mg, and Fe in the progressive metamorphism of argillites. Some cases have been cited (Ramberg, 1952) of the downward concentration of sulphides in basic rocks, much as from basic magmas, and also of titaniferous iron oxides in "metamorphic" anorthosites, due to the instability of titanium in silicate lattices in the granulite facies. How diffusion of metallic ions from heterogeneous assemblages of rocks undergoing metamorphism would lead to a normal rather than a highly repetitive paragenesis, however, is not explained.

No one, as far as the writer is aware, has yet secured or assembled the data necessary to make a thorough analysis of all conditions requisite for the mobilization and later concentration of common ore metals.

Sullivan (1954) has endeavoured to show that *melting points* together with *weak metallic and covalent bonding* may be factors in liberating metals from original minerals during metamorphism, along with the effects of

intrusions and assimilation. One of his Canadian examples will be discussed later. It is difficult to accept the melting points of individual metals as being any more valid in this case than they are in determining the temperature of crystallization of various compounds with which they combine. Probably owing to weak bonding, however, the ready diffusion, under thermal conditions, of copper and iron in specimens containing pyrite, pyrrhotite, and chalcopyrite, is readily demonstrable (Hawley, 1941), in contrast to the relative stability of zinc and lead in sphalerite and galena. As noted earlier, *bonding* and *diadochial factors* should be applicable to recrystallization as well as primary crystallization, but their importance under less intense conditions than those prevailing in magmas needs careful evaluation.

More commonly, the reworking or remobilization of primary ores is considered to be brought about in part by what Schneiderhöhn (1954) aptly terms *secondary hydrothermal solutions*, made available by deep-seated metamorphic processes accompanying orogenies, and in part tectonically, during dynamic metamorphism. The resulting deposits, with which Schneiderhöhn is chiefly concerned in Europe and North Africa, are deposits of epithermal affinity with "monotonous and non-specific mineralogical characteristics." Although such deposits are not of much importance in the area involved here, it is nevertheless interesting to note his classification of them: (1) deposits regenerated orogenically in fissures in the overlying cover, which have been developed by epeirogenic movements and are related to faults in the basement; and (2) deposits in the folded portions of orogenic belts in Europe and elsewhere, affected by repeated orogenies. In the latter group some deposits may have remained fixed, though "deformed and suffused by metamorphism," and others have moved from the deeper, higher temperature zone to be "selectively reprecipitated" in higher horizons in the late orogenic folds, so that all gradations may be found from one to the other. In this group he suggests a further subdivision to distinguish those regenerated in an orogeny *with* and *without* contemporaneous intrusions and subsequent volcanism. Obviously these processes may have been equally effective in modifying and regenerating primary Precambrian deposits, especially in areas affected by more than one orogeny. In such terranes the possibility must be considered as to whether these areas have, wholly or in part, been depleted of their metallic content by transportation to horizons long removed by erosion, or whether primary magmatic (post-metamorphic) mineralization has occurred in such areas at a later time. In other words, do the highly gneissic areas of the Precambrian hold any promise for the further discovery of post-metamorphic ores?

Shaw (1954) in an interesting study of the progressive metamorphism of pelitic sediments endeavoured to determine if disseminated metals were actually lost in the process. He was able to show that nickel decreases to some extent during metamorphism, that copper maintains a constant value up to medium grade metamorphism, followed by a small but constant de-

crease in the highest grade. The validity of the latter trend was questioned, however. Peculiarly, lithium and lead were found to have nearly doubled in metamorphic rocks, but it appears that these may have been introduced during potash metasomatism from a nearby monzonite.

In a study of the metamorphism and conversion of greywackes and basic igneous rocks to green schists, Taylor (1955) has shown that the chemical redistribution of elements (including Cr, Ni, Co, Cu) in both was so slight that chemical data could be used to indicate the nature of the parent rock, and that in what were formerly layered basic intrusives, "the persistence of a primary, uneven, element distribution" was clearly due to gravitational differentiation in a sill prior to deformation and metamorphism. A very similar behaviour has recently been found for Ni and Co in serpentinized ultrabasics in the Yukon by Campbell (1956). The effectiveness of at least low grade metamorphic processes in redistributing such elements may thus be questioned.

Yoder (1955) has recently given a careful analysis of the role of water in metamorphism and shows its dependence on four variables, temperature, rock pressure, water content, and water pressure. He indicates how owing to variations in bulk compositions, it is possible to have, at the same rock pressure and temperature, representatives of several (metamorphic) facies and notes objections "to the concept of the ubiquitous occurrence and adequate supply of water as a free phase in metamorphism." Since water may be a vehicle for the transport of ore constituents this obviously complicates the situation and may account for marked variations in the amounts of metals so removed.

Still another factor which may bear on the subject, in so far as reactions during metamorphism aid in liberating metallic constituents, is Saull's (1955) finding that many metamorphic reactions are exothermic rather than endothermic.

Criteria for the recognition of the "paternity" (after Schneiderhöhn) of such "secondary hydrothermal" or regenerated ores and their ready distinction from primary magmatic ores are necessary. Uytenbogaardt (1953) affirms that ex-solution intergrowths, such as of titanhematite and Fe_2O_3-bearing ilmenite in amphibolitic rocks, could only have developed from solid solutions formed under magmatic conditions. Schneiderhöhn apparently feels, as does the present writer, that the *normal paragenesis* is the outstanding feature of primary ores. The regenerated deposits to which he refers, however, are all of an epithermal type. In zones of greater tectonic intensity, sericitization and chloritization occur, and large quantities of Fe, Mg, Ca, CO_2, H_2O, etc., are thought to pass into solutions, to be eventually redeposited above. Deep tectonic, active, master faults are envisaged as places where solutions from deep deposits and also from enclosing rocks may be concentrated and where deposition might follow in suitable structural traps and host rocks. Many such master faults are recognizable in our Pre-

but, as we shall see, examples showing features of Alpine types, such as iron-free sphalerite, silver-poor galena, manganiferous siderite, and barite, are rare; however, other deposits do exhibit the mineral alterations listed above (albitization, etc.) and are accompanied by carbonates of Ca, Mg, Fe, and quartz. The possibility that the latter are in part magmatic and in part tectonic and/or metamorphic thus requires examination.

Probably one of the best criteria for regenerated or secondary hydrothermal deposits and also for "contaminated" primary deposits is that given by Holmes (1947) and other investigators, as recently reviewed by Wilson, Russell, and Farquhar (1956). This depends on the relative abundances of lead isotopes in galena-bearing deposits from which indications of a derivation from either a single, deep-seated, primary source or from several sources and ages may be had. Results of such studies on galenas from our Precambrian deposits by the latter authors are interpreted as showing quite clearly a single age, and hence a primary source in the mantle for the majority of deposits in any one area or subprovince. Anomalous results in a few imply contamination of primary solutions by adjacent crustal or cover rocks.

This is obviously a complex subject. Clearly a distinction needs to be drawn between the effect of metamorphism on previously formed ore concentrations on the one hand, and its effect on the highly disseminated metallic ions locked up in rock minerals on the other. The relative scarcity of readily recognizable anamorphosed sulphide[1] ore deposits in Canadian metamorphic terranes suggests that anamorphism has either destroyed them or modified them in such a way as to render them indistinguishable from primary ores. The movement of disseminated ions needs further confirmation and at best, one feels would lead to small and widely scattered ore concentrations, but admittedly certain structures might funnel them upward and bring about enrichment, as undoubtedly happens in the case of juvenile solutions.

A further distinction must also be made between such effects of metamorphism *per se* and "contamination" of primary magmatic solutions by both metallic and non-metallic constituents, derived either from the rocks

[1]An interesting example of an anamorphosed (syngenetic) deposit affected by T/P conditions prevailing during granitization is given by Kullerud and Neumann (1953). In northern Norway, near Rendalsvik, a sulphide-bearing band of graphite schist is interbanded with other metamorphosed sediments which grade from mica schist to granitic gneiss and "fairly homogeneous granite." The graphite schist contains 5–10 per cent pyrrhotite and traces of sphalerite which has 12.5 mol per cent FeS in solid solution. From Kullerud's earlier studies the maximum temperature of formation of this sphalerite, at a pressure of 2,000 atmospheres ± 1,000 atmos. appears to have been 440°C. ± 25°C. This is well below the temperature at which granite magmas are believed to form (i.e., 670°C.). The even distribution of sulphides in the schist and absence of hydrothermal and metasomatic evidence indicate an original sedimentary origin for them. As a corollary, one might conclude that under such granitizing conditions, iron and zinc sulphides were *not* remobilized and driven elsewhere from this horizon but remained disseminated in it.

through which these pass or from solutions or ions liberated during contemporaneous and progressive metamorphism. Certain textures and parageneses stand out as typical of primary magmatic ores, but "contamination" of such solutions is indicated by lead isotopes. On the other hand, some epithermal-type ores, in areas where magmatic activity is not evident, show a rather nondescript but nonetheless typical mineral assemblage. If the latter are truly metamorphic in origin, the magnitude of the contribution by metamorphic processes to other deposits remains a question.

Some Precambrian Ores in Ontario and Quebec

There is time here only to take a brief look at some of our Precambrian ore deposits in the Superior (Temiscamian) and Grenville subprovinces of Ontario and Quebec, in the light of the foregoing.

In the Superior subprovince there is geological evidence of at least two important orogenies with which ores are associated: a widespread early Precambrian, pre-Cobalt, or Algoman orogeny during which volcanics and sediments (Keewatin and Timiskaming type) were steeply folded and subsequently intruded by basic and then granitic and porphyritic rocks; and a more restricted (?), late Precambrian orogeny—the Killarnean (= Grenville of Cumming, Wilson, *et al.*, 1955), evident along the north shore of Lake Huron and possibly in the vicinity of Richmond Gulf and south of Ungava Bay (Dresser and Denis, 1944), during which Cobalt and other Huronian-type sediments were folded and intruded by granites and by both pre- and post-granite, basic dykes, and sills. Consideration need not be given to what was probably the earliest of all orogenies—the Laurentian—so far only clearly represented by granitic pebbles in Timiskaming sediments, nor do we see any clear evidence of metallization associated with an intense period of folding in post-Huronian and pre-Keweenawan time (Cooke, 1946), unless the Cobalt silver deposits might be fitted in here.

On the basis of isotopic studies of lead found in deposits in this subprovince, Wilson, Russell, and Farquhar confirm clearly two main periods of lead deposition, one older, of the order of 20×10^8 years, the other younger and ranging from 12 to 15×10^8 years in age. The former corresponds to the Algoman, the latter to ages of pegmatites and leads in the Grenville. (In the Cobalt deposits it is suggested that this lead represents largely older remobilized "Keewatin" lead, mixed with some younger radiogenic lead at the time of the intrusion of the Nipissing diabase, to yield the reported age of 19×10^8 years.) Some anomalous results, as on the Quemont (Quebec) ores and Upper Canada gold (Kirkland Lake), are interpreted as being due to contamination of primary with radiogenic leads.

Equation of the Sudbury nickel-copper mineralization with the Grenville (orogeny), on the basis of lead isotopes in galena which replaces or clearly cuts massive Ni-Cu-Fe sulphides, as well as occurring in late slips, will be acceptable only on the basis that the Sudbury irruptive, later basic dykes, and ores are of a similar age.

In the Grenville subprovince, at least one clear-cut orogeny is indicated geologically, with a possible second, less pronounced, of post-Hastings age. Uplift of this area and erosion accounts for the high grade metamorphic character of the rocks here. Detailed mapping may yet show a more complex history. In this area metallization is largely restricted to lead and zinc deposits, minor molybdenum, titaniferous and non-titaniferous magnetite, and sparse calcitic lead ores. Isotopic studies of Wilson *et al.* indicate the lead-zinc ores to be chiefly 8 to 13 $\times$ 10^8 years old, with one or two—such as New Calumet—somewhat younger.

Although these studies yield the conclusion that most of the deposits under consideration probably represent primary magmatic ores arising from the mantle, and that only a few have suffered contamination by radiogenic lead from the crust, a re-examination of the deposits still seems in order, particularly to determine if any other constituents of the ores appear as mobile as, or more mobile, than lead and to note some of the implications which follow.

Gold Deposits in the Superior Province

The gold deposits extending from Porcupine and Kirkland Lake into northwestern Quebec, associated spatially with great fault zones and other earlier structures, are dominantly quartzose with minor carbonates and sulphides. These exhibit the normal paragenesis of pyrite-arsenopyrite, pyrrhotite, chalcopyrite, sphalerite-galena, and dominantly late gold with or without tellurides. Much of the gold fills fractures in or replaces pyrite and other metallic and gangue minerals. Where galena is present a close age relation between it and gold is suggested by the occurrence of both in segmented veinlets, as with tellurides.

The gold deposits have been emplaced in both folded, sheared, and fractured volcanics and sediments, chiefly of the green-schist facies, and also, in places, in intrusives ranging from quartz porphyries, syenites, and syenite porphyries to albitic granodiorites. In some, the intrusives are chiefly sodic; in others (Kirkland Lake), somewhat more potassic. Adjacent rocks at one or several stages in their history have suffered alteration to albite, chlorite, sericite, ankeritic carbonate, and more rarely tourmaline. Disseminated pyrite, in some cases auriferous, is abundant, and a considerable volume of quartz has been introduced not only in dilatant fractures but also as a replacement of host rocks.

On the basis of both the normal paragenesis and the uniformity of lead isotopes, the conclusion seems sound that these gold deposits have been formed from primary magmatic fluids, rather than by selective leaching of metals, particularly gold, from adjacent and underlying metamorphic rocks by circulating solutions of metamorphic origin.

One must admit, however, that the alterations in adjacent rocks and certain constituents in the ores themselves, such as the albitic character of porphyries, albite within some veins, extensive carbonatization (ankerite)

locally with chromian mica, as in the Porcupine, are identical in character with metamorphic effects in zones of intense tectonic activity, as noted above. Because of their rather similar character these alterations cannot be readily distinguished as to age. Some are undoubtedly due to intense early folding, some to intrusions of porphyry, and some to extensive shearing and faulting. Ore deposition for the most part followed the latter. It is of interest to recall the suggestion of Bowen (1940) that the source of the large volumes of CO_2 requisite for extensive development of such carbonates lay in more deeply-seated carbonate rocks undergoing metamorphism, since the amounts are far greater than could be expected either in intrusives themselves or in the originally fresh, basic to intermediate volcanics. Of course, no such carbonate rocks are known to underlie Keewatin lavas and whatever the source of the CO_2, the Ca, Mg, Fe, and Na may well have had a metamorphic derivation. Some would also argue that most of the quartz was similarly derived (Boyle, 1955), and that the relatively small amount (5–15 per cent) of sulphides, chiefly pyrite, might have had their metals similarly supplied, and if all these, why not the gold, tourmaline, and scheelite? Could the constancy of lead isotopes in galenas indicate remobilization of lead from only one age of rocks such as the porphyries? Could the gold likewise have had a source in either the porphyries or the original lavas? The geothermal control about the larger porphyry intrusives in Porcupine (Smith, 1948), on the deposition of both scheelite and auriferous pyrite, suggests a genetic, though not necessarily a magmatic, as compared with a metamorphic, origin. Can it be shown by utilizing radioactivation methods of analysis for gold in igneous rocks (Vincent and Smales, 1956) that an actual impoverishment has occurred in such rocks? And how may the occurrence of barren and auriferous quartz veins in close proximity be explained under the metamorphic theory, when examination of the quartz itself shows no marked difference in fluid inclusions and temperatures of decrepitation?[2] Answers to these questions are obviously needed and until they are available the many complexities cannot be fully resolved.

To the east, in both the Kirkland Lake and western Quebec areas, gold deposits with local variations in mineral content, but all with a normal paragenesis, again, are intimately associated with deep faulting of lavas, sediments, and intrusives. Such lead isotopic studies as are available indicate a very uniform and probably single age (Wilson *et al.*). At Kirkland Lake syenitic intrusives, the dominant host rocks, show a typical ankeritic, chlorite, sericite alteration, as do shear zones at Kerr Addison. Tellurides are a feature of Kirkland Lake. Farther east gold-sulphide replacements occur within schist zones themselves while in the Siscoe-Bourlamaque area "granodioritic" intrusives form the chief hosts and are highly albitized (Gussow, 1937) in the vicinity of quartz-tourmaline, gold-bearing veins.

Thus in all, there are indications of one extensive period of gold deposi-

[2]R. V. Oja and F. G. Smith, personal communication.

tion related clearly to deep faulting and probably to deep magmatic sources. Local characteristics in any one camp (scheelite with less tourmaline and tellurides at Porcupine; tellurides at Kirkland Lake; abundant tourmaline at Bourlamaque) seem attributable to local variations in associated intrusives, where present and the ores may well have had their source either in parent magmas below or in the intrusives nearby. Alterations of wall rocks to varying degrees accord with those common in regional metamorphism, and such processes may have contributed, but likely in a minor way, to the substance of the deposits themselves.

Base Metal Deposits

The widespread copper-iron ($\pm$ zinc) sulphide deposits extending from the Geco deposit in northwestern Ontario to Chibougamau in Quebec, on mineralogical grounds, may all be grouped together. All show essentially the normal paragenesis. All are dominantly replacement and large replacement bodies; many, if not all, are in proximity to deep faults of great extent, and also to granitic (magmatic) intrusives. They are at the same time distributed relatively close to diabasic intrusives, the pre-ore or post-ore age of which is still not clearly settled in all cases, although the latest are placed in the late Precambrian. The older host rocks have been regionally metamorphosed to at least the green schist facies prior to ore deposition, but chloritization, sericitization, and silicification are recorded as extensive in the vicinity of the ores.

Some local variations in content, for example, the ratio of copper to zinc, and arsenic to sulphur, gold, and tellurides, are well known. Others are indicated by spectrographic studies, such as traces of tin in chalcopyrite of the Geco deposit (F. F. Langford, 1955), and the amount of cobalt in pyrite (Allard, 1953), especially in the Chibougamau district.

On geological grounds the ages of these deposits have been considered as late Precambrian. On the other hand, lead isotope determinations by Wilson *et al.* indicate a very early Precambrian age for deposits at the two ends of the belt (Geco, 26×10^8 years, and the Campbell-Chibougamau, 20×10^8 years). For the more central Noranda district, where galena is very rare, anomalous leads suggest contamination from crustal rocks, as at Quemont. One might suggest, however, that the indicated age for some of these deposits, as noted by Wilson *et al.* for the Cobalt deposits, are greater than they should be due to contamination from "Keewatin leads." In any case, whatever their true age, some contamination of primary ore fluids seems indicated even if only for such a minor constituent. A somewhat similar derivation for minor silver in sulphides in an occurrence of disseminated pyrite and chalcopyrite, north of Noranda, has been detected by Hogg (1952). Careful separation of altered andesite from such sulphides gave negative silver in contrast to positive silver in unmineralized andesite. The inference seems clear that during mineralization silver migrated with sulphur and became incorporated with the sulphides.

Although no one, so far as the writer is aware, has ever suggested that these deposits are other than primary and hypogene in origin, it seems possible that certain local but only minor characteristics, such as their tin, gold (?), silver and cobalt content, have been acquired locally, as seems to be the case for anomalous leads. These additions need in no way have been due to metamorphic processes alone, but to contamination of primary ore solutions arising from deep gabbroic sources tapped by great faults.

Nickeliferous Copper Deposits of Sudbury

The geological features of the Sudbury area are perhaps still in too much a state of flux to allow a detailed discussion of the origin of these famous ores. Their basic magmatic affiliations appear so clear to some of us that argument on this point seems superfluous, whether they were derived from the nearby norite or its parent magma below. Their massive to disseminated sulphide character, their nickel, cobalt, and platinum metals content, high temperature features (ex-solution textures in pyrrhotite, cubanite and others), and general lack of hydrous silicates, carbonates, and quartz, indicate an ore fluid dominantly of a metal-sulphide type but one still capable of extensive replacement of silicate rocks. To quote the latest opinion of Sudbury geologists (1953), however, while "the balance of evidence favours the . . . accumulation from the nickel intrusive during a process of differentiation," as against an introduction after the norite had solidified, ". . . the final analysis may prove neither explanation is wholly correct."

Two other views should be noted. One, put forward by Sullivan (1954), suggests that, on the basis that the norite is separated in time from the ore at Creighton by both Creighton granite and quartz diorite intrusions (after Yates, 1948), the ores, or at least the metals, were liberated from assimilated silicates of the norite, which was caught up in the granite, and diffused towards the quartz diorite which formed by recrystallization between the two. In view of later work by Sudbury geologists (Speers, 1956), it seems fairly clear that the main bulk of the Creighton granite is *pre-norite*, that breccias within it have, in fact, suffered thermal metamorphic effects attributable only to the norite, and that at least some of the granite-like dykes penetrating norite are really granitized, highly comminuted "injection breccias" which were later recrystallized. If this is so, Sullivan's theory collapses.

A second theory is held by Wilson *et al.* (1956), whose studies on leads from the Sudbury area show they fall into two groups, one of about 12×10^8 years, the other, anomalous and explainable by contamination with radiogenic leads. The ores are considered as having risen "from the mantle along faults . . . near the border of the rising Grenville mountains" and would thus appear separated in time from associated basic intrusives which themselves have suffered some post-ore faulting. Paragenetic studies clearly indicate that galena within the massive sulphide ore bodies occurs: (1) as a relatively late mineral intergrown with parkerite, a Ni-Bi sulphide;

(2) as crosscutting veinlets, intergrown with sphalerite; and (3) as at Falconbridge, along chloritic, post-ore slips, which may be even later. To thus date the whole of the ore bodies, and at the same time their associated intrusives, is perhaps questionable.

What is of interest in the present discussion, however, is the indication of contamination of some of the mineralization with radiogenic leads. This being true, it is not unreasonable to suppose that some other constituents of the ores have also been contributed in a similar way. Taking into account the more widespread Keweenawan copper mineralization extending from Michigan along the North Shore of Lake Huron through to Sudbury, if it is all of one age, one might imagine a similar "contamination" of primary copper-iron-sulphide fluids by nickel from the Sudbury irruptive. There is as yet no clear evidence to distinguish mineralogically between ores formed by such a combination of processes and ores arising from Cu-Ni-Fe fluids related to a more local basic magma either *in situ* or at depth. Geologically, however, the spatial and structural relations of such ores to the base of the norite and, in particular, as at the Frood (Yates, 1948), to a downward tapering wedge of quartz diorite (a phase of norite) makes it impossible to accept anything but a dominantly local and magmatic origin for them.

Grenville Deposits

In the more deeply seated, more intensely metamorphosed Grenville terrane it is not surprising that metallic deposits are of a different type and of rarer occurrence than in the contiguous Superior subprovince, on the basis both of degree of metamorphism and, if we follow Wilson, of their younger age. Missing are the numerous gold and copper deposits, although minor, economically insignificant deposits of these are known. Instead, there are a few massive and disseminated sulphide deposits of the high-temperature lead-zinc type; widely scattered and seldom economic deposits of molybdenite, associated with pegmatites and granitic rocks;[3] important non-titaniferous magnetites, minor ilmenites (in Ontario) with gabbros; and again a rather diverse scattering of calcite-barite-celestite veins with galena and lesser sphalerite, rare fluorite and a crustification, suggestive of lower temperature deposition and epithermal affiliations.

The high-temperature type of lead-zinc deposits—Calumet and Anacon—has recently been dated by Wilson *et al.* as about the equivalent of Grenville pegmatites ($8–13 \times 10^8$ years). These have been emplaced in highly crystalline rocks, gneiss or crystalline limestone, are post-metamorphic, show a normal paragenesis, and thus have the characteristics of primary ores arising from depth. Depending on the origin assigned to the pegmatites and granites, the molybdenite deposits may be ascribed to either magmatic or granitizing fluids. The titaniferous magnetites, in Ontario, associated with gabbroic intrusives, and the important ilmenite deposits at Allard Lake,

[3]Uranium deposits, associated with similar rocks, are omitted from this discussion as study of their genesis is in progress. Also omitted are some recently discovered nickeliferous sulphides in gabbroic rocks.

Quebec, associated with anorthosite, seem best explained by magmatic processes, although the anorthosite problem needs re-examination. The nontitaniferous magnetites, of current interest in both Ontario and Quebec, spatially related to granitic and syenitic masses, and heretofore usually considered of magmatic derivation, we might note, were thought by Miller (1894), and later by Jones (1953), to have a metamorphic derivation from nearby scapolitized diorites. Some granitization of gabbroic rocks has clearly occurred and further study of these ores associated with actinolite, hornblende, and diopside may well reveal a metamorphic rather than magmatic history.

Similarly the correspondence of the calcitic lead-zinc vein deposits to Schneiderhöhn's regenerated Alpine deposits suggests that these might here be due to regeneration by secondary hydrothermal solutions, possibly during the Appalachian orogeny, of metals from deeper deposits and gangue from some of the host rocks.

A study of trace element content in Grenville rocks—granites, gneisses and amphibolites—is under way in our laboratories, but is still too incomplete to allow a statistical comparison to be drawn between them and average granite and gabbro. Such data as we have from Ontario occurrences indicate that Grenville granites, at least some of which are products of granitization, are little different from the average granite in Pb, Ag, Cu, Co and Cr, but have about half the Ni of the latter. A few analysed amphibolites and biotite-rich gneisses show a content of Cu, Ni, and Cr much the same as average gabbros, but with about half the Co. The content of these metals in original Grenville sediments and volcanics is not determinable, and accordingly it cannot be shown that such metals have been lost during high grade metamorphism. Metamorphic processes involved, however, do not appear to have depleted the resulting rocks beyond the concentration of these elements in average granite and gabbro, and unless there were sedimentary concentrations of metals in the original rocks, one may question the efficiency of such processes in the making of new ores in this as well as other areas.

Conclusions

A review of magmatic and metamorphic processes indicates that both may play a part in the concentration of ore fluids and resulting deposits. Of the two, the former seem much the more efficient and likely, especially in areas which have suffered, in sequence, regional or higher grades of metamorphism, magmatic intrusions, and mineralization; the same is true for an explanation of their textures and paragenesis. Metamorphism may undoubtedly be effective in redistributing former ore deposits, and in the formation of some of the more diffuse and generally smaller "secondary hydrothermal" deposits in areas where contemporaneous vulcanism is missing. There are also indications that *either* metamorphic *processes or* metamorphic *products* may contribute to or contaminate primary magmatic ore

fluids rising from great depths, but it is not clear how a distinction may be drawn between them. Positive evidence that traces of ore-forming ions are effectively separated and concentrated from a dispersed state in silicates during both low and high grade metamorphism is lacking, and in some cases cited, the opposite seems to be true.

Epigenetic deposits in the Precambrian of eastern Canada tend to confirm these conclusions. Algoman hydrothermal gold deposits, widespread major copper-zinc deposits, and Sudbury nickel-copper ores show by both geological and mineralogical features a derivation from primary magmatic fluids and rather local but minor "contamination" with either distinctive trace metals or gangue constituents. The manner of "contamination" cannot be distinguished with any certainty. The high-temperature type of lead-zinc deposits in the Grenville subprovince is similarly interpreted. There is much to be said for a source deep in the mantle, tapped by major faults, as compared with more local magmas, with the possible exception of the Sudbury ores. The implication from this is that though local structures and favourable host rocks are essential, the grade of metamorphism of adjacent rocks is of lesser consequence in the formation of ores.

In the Grenville granitic and gneissic areas re-examination of abundant but scattered deposits of molybdenite and larger deposits of magnetite should be made to see how important granitization processes have been in their genesis. A few minor galena-calcite vein deposits in southeastern Ontario are very similar to Schneiderhöhn's secondary hydrothermal, regenerated Alpine types.

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SECTION FOUR

Dating Cordilleran Orogenies

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ABSTRACT

Potassium-argon dates for a number of volcanic and plutonic igneous rocks from the North American Cordillera suggest that the principal mesozoic intrusives may be late Cretaceous in age (Laramide), rather than Jurassic (Nevadan). Sanidine from the Crowsnest volcanics, Alberta, of Mid-Cretaceous age, gives a potassium-argon age of 96 m.y. Two samples of granitic rocks and a feldspar phenocryst from the Sierra Nevada batholith (California) gave ages of 88, 72 and 68 m.y., similar to a 71 m.y. age obtained for orthoclase from the Laramide Boulder batholith (Montana). A study of heavy mineral residues from the Cretaceous sedimentary section and comparison with those from the Cordilleran intrusives suggests, however, that during Lower Cretaceous time granitic intrusives were emplaced and unroofed in the Cordilleran area. The 105 m.y. lead alpha-activity age of zircon separated from the Nelson batholith (British Columbia) indicates that it may have been one of these early plutons.

Introduction

JELETZKY (1956), who has presented the case for palaeontology as the basis for practical geochronology, relegates physical age determination methods to a distinctly secondary role: "They all have only theoretical and educational value in providing some crude, but nevertheless

TABLE I
SUMMARY OF AGE DATA

Physical time (Holmes B Scale)		Locality	Cordilleran dates	
			Feldspar (K/A)	Zircon(Pb/α)
58 m.y.	Tertiary Laramide			
		Boulder batholith	71*	70†
	Upper Cretaceous	Sierra Nevada batholith	67–88	90–109†
		Crowsnest volcanics	96	
	Lower Cretaceous	Nelson batholith		105
127 m.y.	Nevadan Jurassic			

*Assuming $R = 0.12$, $\lambda = 0.51 \times 10^{-9} y^{-1}$.
†Larsen *et al.* (1954).

*J. H. Reynolds and J. Lipson of the Department of Physics, University of California, Berkeley, contributed the potassium-argon age determinations reported in this paper.

most welcome data which give a degree of insight into the duration of geological processes and the distances of geological events from one another, in terms of the physical time."

The practical geochronology of this paper is based entirely on physical age determinations, using radioactive isotopes. The results have been checked by the methods of sedimentary petrology. Strangely, the account (Table I) seems to be in complete accord with the relative geochronology of the Cretaceous of Western Canada as established by the work of palaeontologists and stratigraphers such as Warren and Stelck (1956).

The physical age determinations are based on study of the isotopes of two radioactive elements, potassium and uranium. The dates are in relatively good agreement, which lends further support to their validity.

Geochronology

Our problem, briefly, was to relate in time the batholithic intrusives of the Cordillera with the generally fossiliferous Mesozoic and Cenozoic sedimentary rocks of the Alberta basin (Fig. 1). An index fossil can be used as a common time factor to establish correlation, and a group of index fossils can be used to build up a time scale. In an analogous fashion, we attempted to use potassium-argon dates from orthoclase feldspars to establish the relation between the Sierra granites (type Nevadan), the Boulder batholith (type Laramide), and the Crowsnest volcanics of Mid-Cretaceous age. Of these three rock masses, only the Crowsnest volcanics can be accurately correlated with the palaeontologically controlled time scale (H. N. S. Mackenzie, 1956). The Boulder batholith, for example, has been variously dated by competent geologists as Archean (S. F. Emmons, 1885), Jurassic (Lindgren, 1886), Miocene (Weed, 1899) and Upper Cretaceous (Knopf, 1913). The Jurassic age assigned to the Sierra Nevada batholith is based on indirect geological evidence (Taliaferro, 1942), and the strength of the geological argument has been greatly weakened with the discovery of a Cretaceous ammonite in the type section of the supposedly Jurassic Franciscan sediments (Schlocker, Bonilla and Imlay, 1954).

There is a great and growing body of evidence to suggest that the principal Cordilleran igneous intrusives may have been emplaced in Cretaceous time: Armstrong (1946); Larsen, Gottfried, Jaffe and Waring (1954); Smith and Stevenson (1955); Wisser (1954). This is in disagreement with the opinion which is rather firmly entrenched in the literature (Taliaferro, 1942; Dunbar, 1949; Eardley, 1951; and Jeletzky, 1954) that the principal period of Mesozoic igneous intrusion in the North American Cordillera occurred in Jurassic time and constitutes the Nevadan or Nevadian (Blackwelder, 1914) orogeny.

The potassium-argon ages of Cordilleran feldspars support the first hypothesis and indicate initiation of igneous intrusion in Mid-Cretaceous time, about 100 million years ago, and its continuation until the close of the

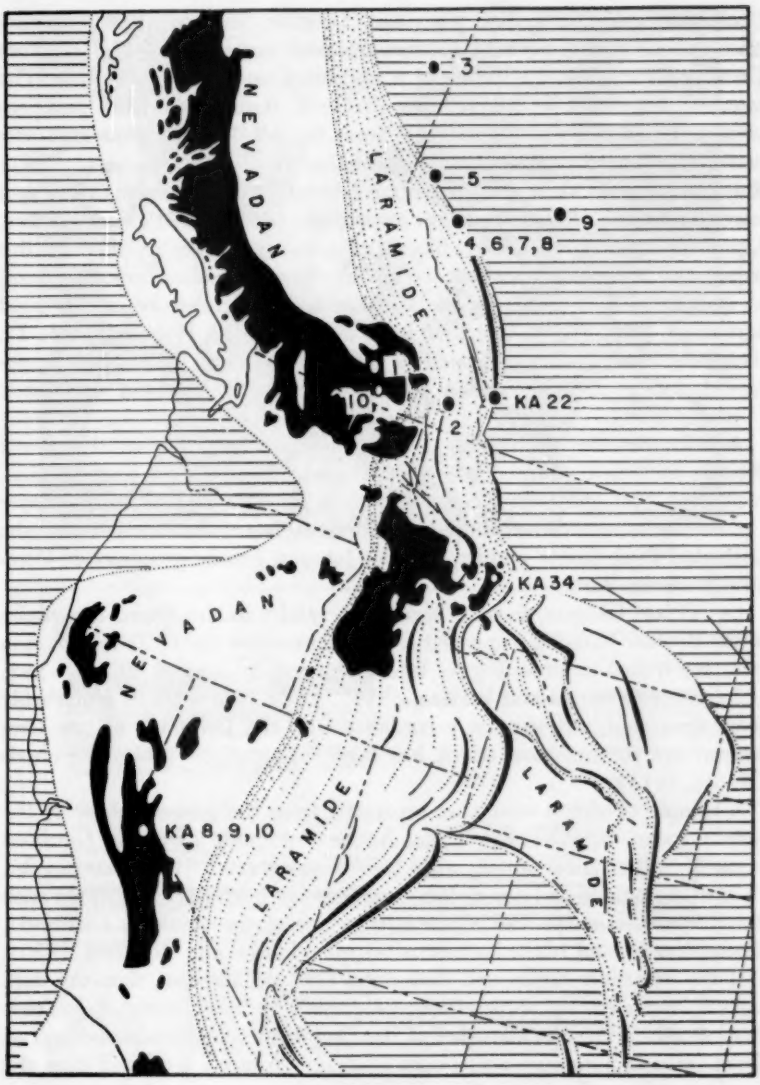

FIGURE 1.—Index map showing the relation of samples studied to the Nevadan and Laramide orogenic belts (after Eardley 1951).

Cretaceous about 70 million years ago. Sanidine (high-temperature orthoclase) phenocrysts from the Crowsnest volcanic agglomerate (Fig. 2), from Crowsnest Pass, Alberta, returned a potassium-argon age of 96 m.y. The sanidine from this waterlain agglomerate is remarkably fresh and unweathered. In calculating these ages from the A^{40}/K^{40} ratio, the constants used are those called for in a compilation by P. M. Hurley (1956): $R = 0.12$, $\lambda = 0.51 \times 10^{-9}y^{-1}$. Potash feldspars give potassium-argon ages lower than those of micas from the same rocks (Wetherill, 1955; Folinsbee, Lipson and Reynolds, 1956). The potassium-argon ages reported in this paper may be about 10 per cent too low in terms of absolute time. However, an age of 96 million years for the Mid-Cretaceous seems to be in very good agreement with the absolute time scale as set forth by Holmes (Table I), though Holmes's figures are based on rather sparse data. Recent geochronological dating of sediments in general supports the Holmes time scale (Lipson, 1956).

A microperthite phenocryst and two granitic rocks from the Sierra Nevada batholith returned potassium-argon ages of 68, 72 and 88 m.y., suggesting that the Sierra Nevada batholith is, in part at least, Upper Cretaceous in age. The samples came from late Nevadan plutons, the Cathedral Peak biotite granite, and the Johnson granite porphyry of Yosemite National Park.

Orthoclase feldspar, from a pegmatitic veinlet in the quartz-monzonite of the Boulder batholith, returned a potassium-argon age of 71 m.y. Zircon from the quartz-monzonite gave lead alpha-activity ages of 69 to 71 m.y. (Chapman, Gottfried and Waring, 1954). These figures are in remarkably good agreement and seem in accordance with the Laramide or late Cretaceous age for intrusion which has been suggested on geologic grounds (Knopf, 1913).

A sample of zircon which we separated from the gneissic phase of the Nelson batholith, Whatshan Lake, British Columbia, dated by Gottfried of the U.S. Geological Survey, gives the following data: 310 alphas/mg/hr, 13 and 14 ppm Pb and age of 105 m.y. This age is in exact agreement with the 105 m.y. average lead alpha-activity age of the southern California, Sierra Nevada, and Idaho batholiths (Hurley, Larsen and Gottfried, 1956).

If the potassium-argon and lead-alpha ages are absolute, then the data suggest emplacement of the Nelson batholith in late Lower Cretaceous time, shortly before the extrusion of the Crowsnest volcanics. However, our Sierra Nevada potassium-argon ages (average 76 m.y.) are lower than the zircon ages from the Sierra Nevada (103 m.y. average) and the ages may not be strictly comparable (Hurley, Larsen, Gottfried, 1956). We believe it is likely that the Sierra Nevadan rocks and mineral separates, for which we have potassium-argon dates, represent later phases of the intrusion than those for which the lead alpha-activity ages are available. In a similar geologic setting, Harrison Lake area of British Columbia, Crickmay (1930) clearly recognized an early concordant granodiorite intrusive which he

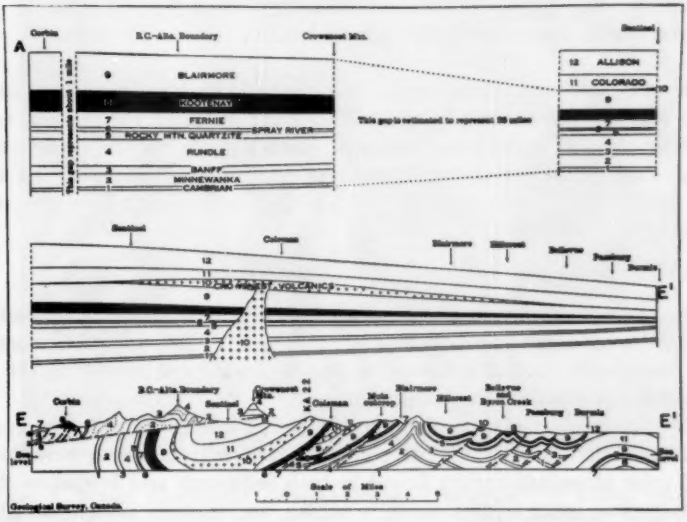

FIGURE 2.—Fragmental sanidine phenocrysts in Crowsnest agglomerate from outcrop west of Coleman, Crowsnest Pass, Alberta. This sanidine, K.A. 22, gave a 96 m.y. potassium-argon age.

believes to be Jurassic, and a later discordant quartz-diorite intrusive which he assigns to the Cenozoic. He emphasizes the lack of discordance between the Jurassic and Lower Cretaceous sediments, but fails to draw what seems a possible conclusion, that the Coast Range granodiorite is Mid-Cretaceous in age.

In summary, it might be said that the geochronological data suggest a main period of Cordilleran batholithic emplacement in Mid-Cretaceous time, 100 million years ago, and a late phase of magmatic intrusion in early Laramide time, 70 million years ago.

Sedimentary Petrology

Accessory mineral determinations were made on samples from five intrusive rocks of the Cordilleran orogenic belt, and also on samples from eleven sedimentary rocks of the Alberta foothills region. The intrusive rocks include: Nelson granodiorite (1), Coryell syenite (10), Ice River syenite, Purcell diorite (2), and Boulder monzonite (KA 34). The sedimentary rocks include: Rocky Mountain sandstone, Cadomin conglomerate (4), McDougall-Segur conglomerate, Crowsnest tuff (KA 22), Dunvegan sand (3), Cardium sand (4), Solomon sand (5), basal Brazeau sand (6), middle Brazeau sand (7), Foothills sand (8), and basal Paskapoo sand (9). Numbers in parentheses refer to sample localities shown on the index map (Fig. 1).

The sedimentary rock samples were crushed, washed in boiling water, and screened. The portion between 60 and 200 mesh was separated, using a combination of gravity and magnetic methods with heavy liquids and a Frantz isodynamic separator. Permanent mounts of these separates were then prepared in aroclor ($n \approx 1.66$) and the petrographic examination made.

Amphibole

The amphiboles are moderately magnetic and most grains are obtained from the concentrates at a current strength of 0.75 amps. Typical form is long-bladed, fibrous, and columnar although rounding of some grains in the sediments has obscured the normal habit.

Three varieties of amphibole were recognized in these samples: common hornblende, arfvedsonite, and blue-green hornblende. Common hornblende is the most abundant variety found in both sediments and intrusives. It is generally deep green to olive-green to brown, and strongly pleochroic. Black opaque inclusions are common and these may be arranged along cleavage cracks or crystallographic axes in the crystals. Arfvedsonite, recognized by its characteristic pleochroism from blue to lavender, or pink to yellowish green, was seen in only two samples, namely the Ice River syenite and the Cardium sand. Blue-green hornblende occurs in the sediments containing other minerals from high-rank metamorphic terranes.

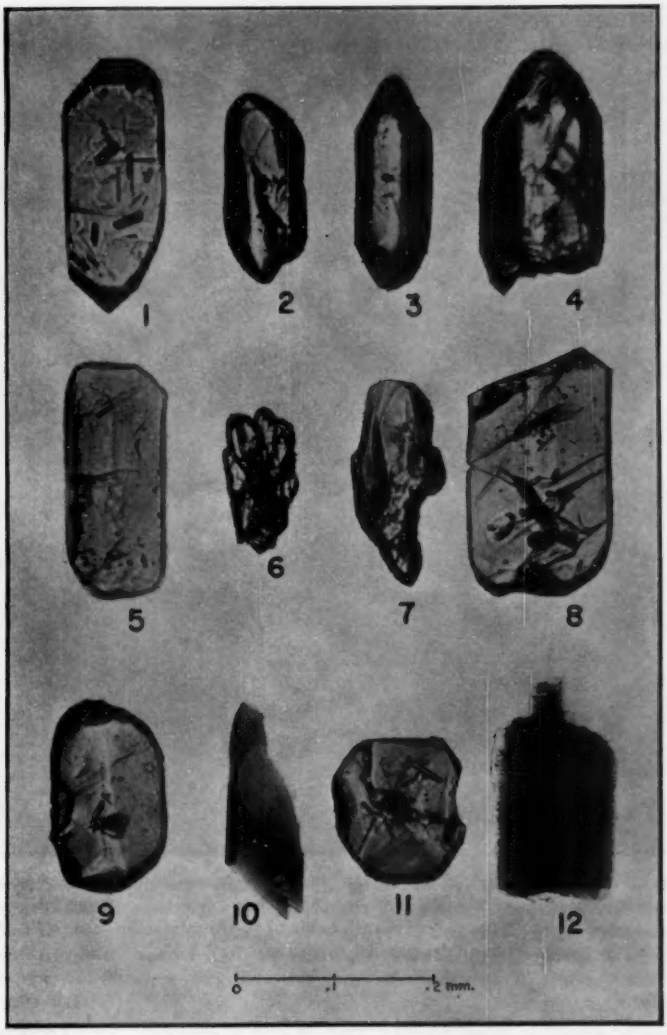

PLATE I. Nelson granodiorite (Albian) accessory minerals. (1) Zircon euhedron: typical form and rod-shaped apatite? inclusions. (2) Zircon euhedron: deep fissure. (3) Zircon euhedron with few inclusions. (4) Zircon euhedron: surface fissures and exposed cavities. (5) Apatite euhedron with few inclusions. (6) Cluster of zircon euhedra. (7) Zircon euhedron: well-developed outgrowths. (8) Sphene euhedron: cracks, exposed cavities, and minute inclusions. (9) Sphene euhedron: opaque inclusion and rod-shaped apatite? inclusions. (10) Augite, dentate termination. (11) Sphene, similar to (9), showing abundant inclusions and rounded euhedral form. (12) Augite: cleavage and opaque inclusions.

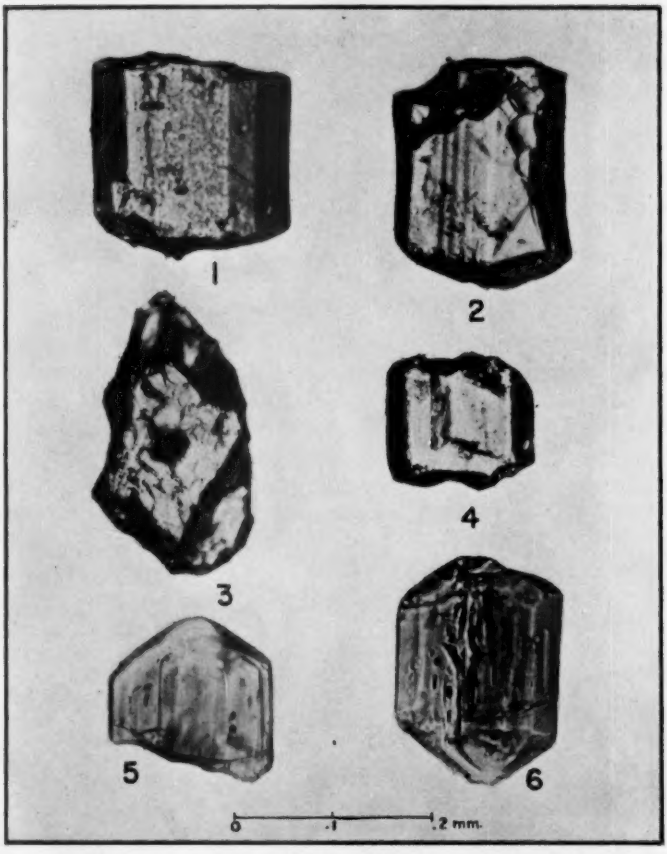

PLATE II. Crowsnest tuff (Late Albian) accessory minerals. (1) Sphene euhedron. (2) Sphene euhedron: conchoidal fracture. (3) Sphene fragment: opaque inclusion and surface fissures. (4) Sphene "envelope" habit. (5) Apatite euhedron. (6) Apatite euhedron: inclusions and cavities parallel to *c*-axis.

Apatite

Apatite occurs in most samples studied and is generally very abundant in the non-magnetic fractions of the concentrates. It is recognized chiefly by its lack of colour, lack of relief in the aroclor mounts and grey interference colour. Irregular cracks are common in some of the more worn grains. These cracks are frequently stained deep yellow. Inclusions and cavities are very abundant in the apatite and include spherical-shaped cavities, rod-shaped inclusions, black opaque spherical mineral inclusions and black opaque dust. These inclusions may be arranged parallel to the crystallographic *c*-axis (Plates II–6; VI–4, 8; VIII–1; X–8).

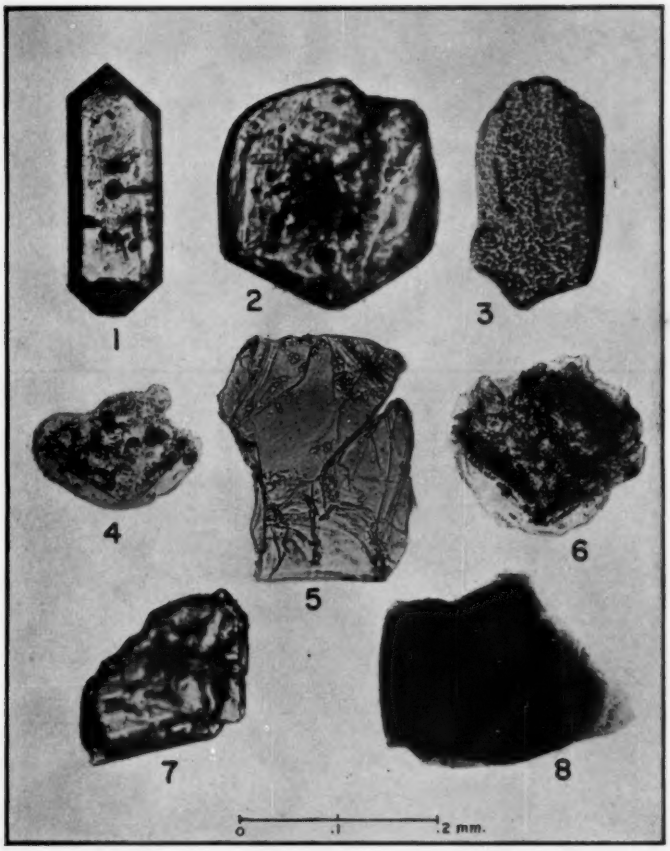

PLATE III. Dunvegan sand (Cenomanian) accessory minerals. (1) Zircon euhedron: crystal form and opaque and straw-like inclusions. (2) Garnet euhedron, slight degree of rounding. (3) Garnet grain, solution etching. (4) Feldspar: original euhedron and abraided overgrowth; opaque dust and inclusions common. (5) Muscovite flake: cracks and cavities. (6) Feldspar euhedron and abraided overgrowth. (7) Garnet fragment. (8) Biotite flake.

Chlorite

Chlorite occurs in most sand samples but is abundant in none. It does not occur in the Rocky Mountain sand or Cadomin conglomerate. It is fractionated at a current strength ranging from 0.35 amps. to 0.75 amps. In general the colour is emerald to yellowish green, weakly pleochroic (most chlorite has distinct pleochroism) with an index about 1.60. The form is usually platy and under polarized light most grains show aggregate polarization. Some grains, however, appear isotropic.

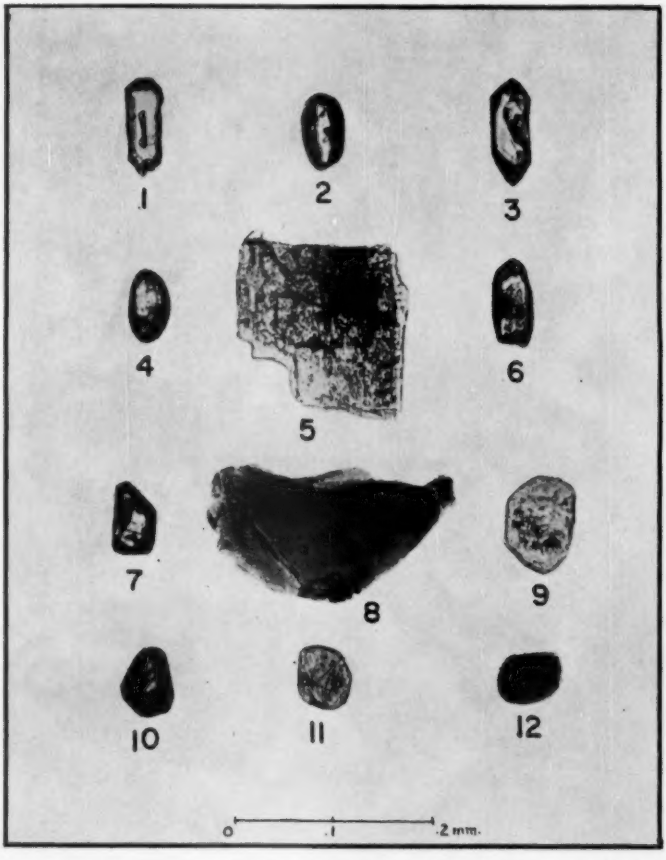

PLATE IV. Cardium sand (Turonian) accessory minerals. (1) Zircon euhedron with inclusion parallel to *c*-axis. (2) Zircon, showing degree of rounding, cavities, and inclusions. (3) Zircon euhedron: exposed cavity. (4) Hyacinth zircon: high degree of rounding. (5) Augite grain: cleavage, inclusions, and staining. (6) Zircon euhedron: slight degree of rounding. (7) Zircon grain. (8) Biotite flake, inclusions. (9) Slightly rounded apatite euhedron. (10) Rounded rutile. (11) Rounded tourmaline. (12) Tourmaline, same as (11), showing dark pleochroism.

Epidote

Epidote is common to abundant in all samples with the exception of the Nelson granodiorite, Crowsnest tuff, Rocky Mountain and Cadomin sands, and Creston quartzite. It is paramagnetic and occurs generally in the 0.45 amps. magnetic fraction. Two varieties predominate: a typical yellowish green variety and a nearly colourless variety. The yellowish green form is

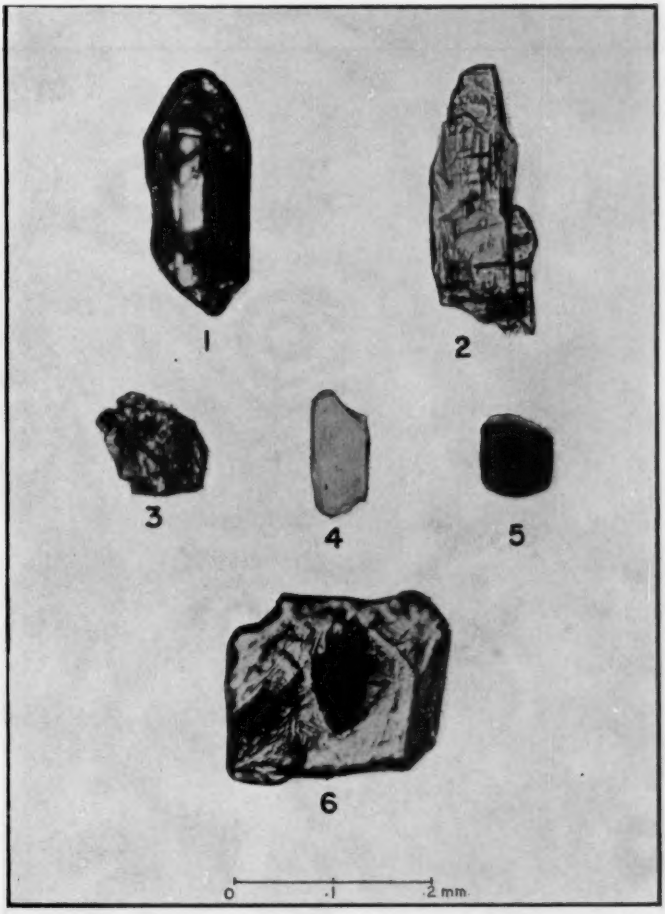

PLATE V. Solomon sand (Late Santonian) accessory minerals. (1) Zircon euhedron. (2) Kyanite grain: elongate form and cleavage cracks. (3) Garnet: fractures. (4) Apatite euhedron with few inclusions. (5) Brown tourmaline, rounded with opaque inclusions. (6) Sphene, showing form and large exposed cavity.

the more common and exhibits strong pleochroism to brownish shades of green. The nearly colourless variety is not as strongly pleochroic as the coloured type but does vary to pale yellowish green. This latter variety is generally very clean (free from stains or inclusion). Angular to round, oblate grains predominate in the sediments and in some cases cleavage parallel to (100) is developed (Plate VI–7); this, however, is exceptional.

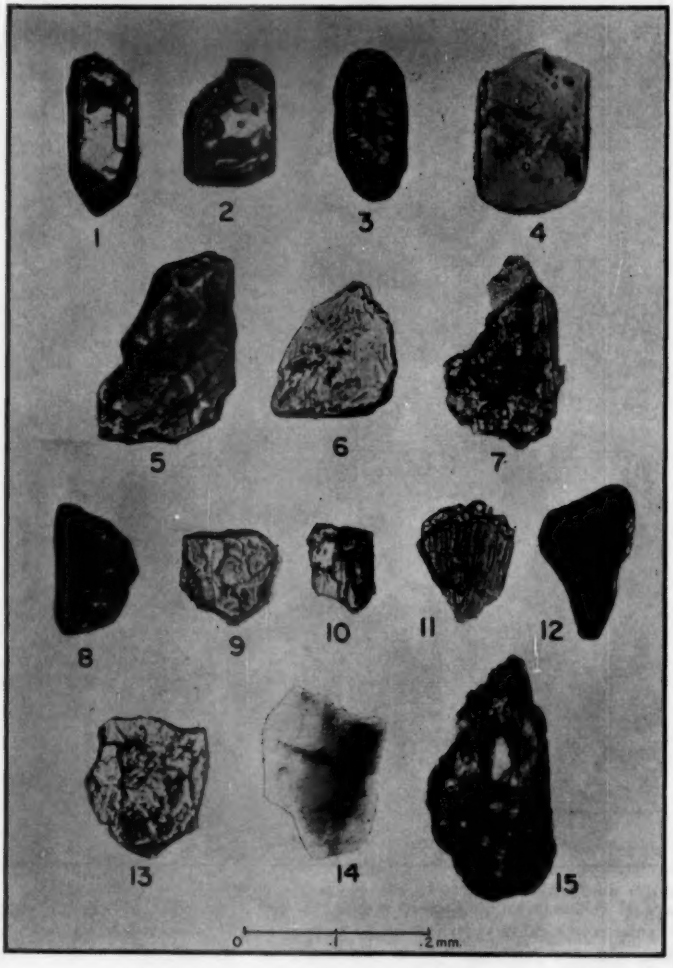

PLATE VI. Basal Brazeau sand (Campanian) accessory minerals. (1) Zircon euhedron (2) Zircon grain: exposed cavities. (3) Hyacinth, rounded. (4) Apatite euhedron: inclusions and cavities. (5) Epidote grain: fractures. (6) Epidote grain: slight rounding. (7) Epidote grain: opaque staining and pronounced cleavage. (8) Rutile, slightly rounded. (9) Zoisite. (10) Zoisite: vertical cleavage. (11) Hypersthene: anomalous radiating cleavage. (12) Tourmaline, slightly rounded. (13) Garnet. (14) Diopside, cleavage infilled with opaque material and inclusions. (15) Sphene: fissures and rounding.

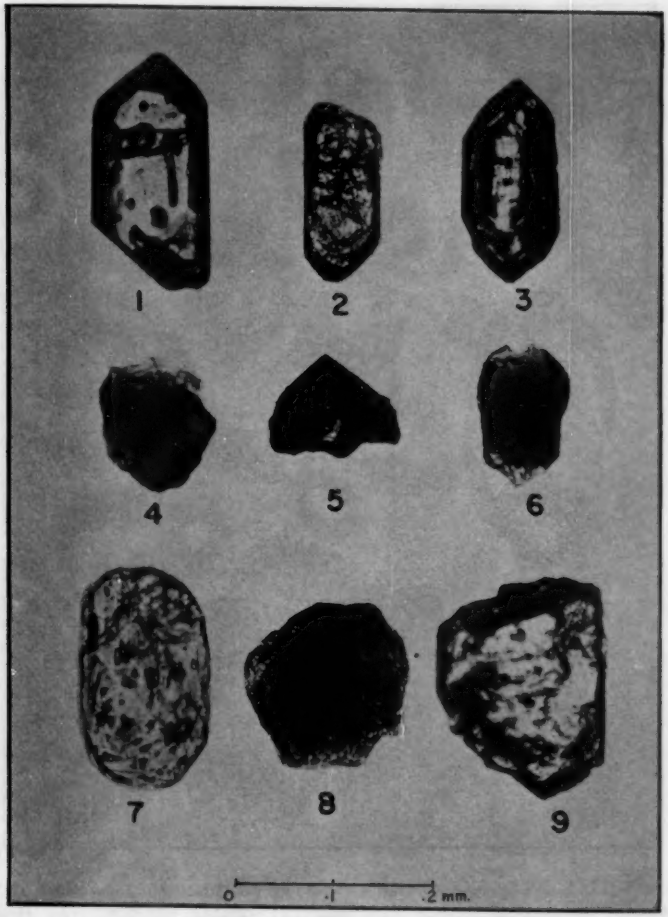

PLATE VII. Middle Brazeau sand (Campanian) accessory minerals. (1) Zircon euhedron: cavities and inclusions. (2) Hyacinth: zoning, opaque inclusions, and anastomosing micro-fissures. (3) Zircon: zoning. (4) Staurolite. (5) Rutile: pyramidal termination. (6) Staurolite: conchoidal fracture. (7) Rounded apatite euhedron: cavities and inclusions. (8) Staurolite: cleavage, opaque microlites, and staining. (9) Sphene.

Garnet

Garnet is second in abundance only to the opaque minerals in the sediments, but is rare to absent in the intrusive rocks. It is more strongly magnetic than epidote, being attracted at a current strength of 0.35 amps. The two most common varieties seen in the garnet fraction are the colourless and the pink types. Other shades include pale brown, pale green, yellow and

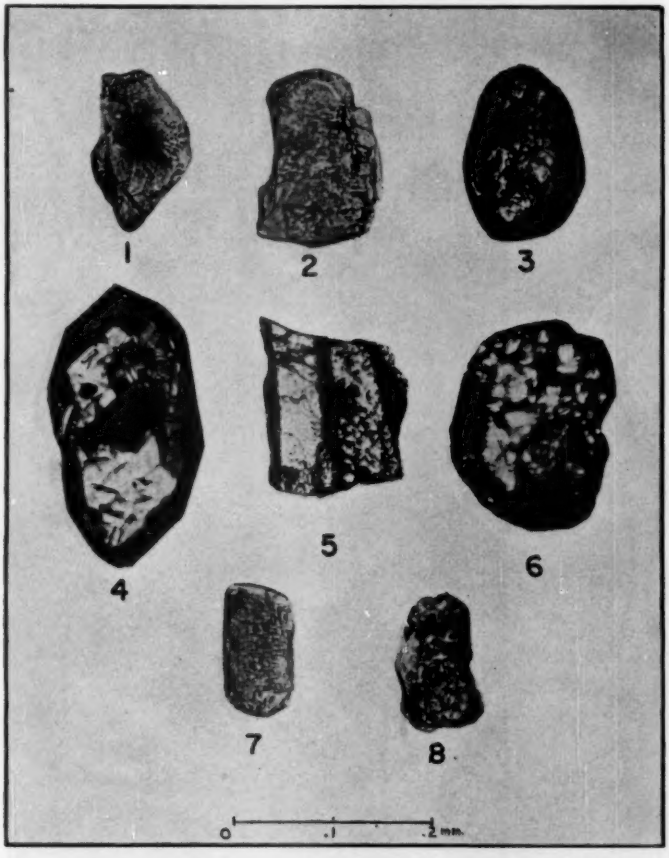

PLATE VIII. Foothills sand (Latest Cretaceous or Palaeocene) accessory minerals. (1) Apatite, network of opaque inclusions. (2) Apatite euhedron. (3) Hyacinth, rounded and fissured. (4) Zircon euhedron: large black cavity and rod-shaped apatite? inclusions. (5) Garnet, some etching. (6) Sphene, rounded and cracked. (7) Tourmaline: pale brown euhedron, inclusions. (8) Apatite, stained.

orange, but these are rare except in the basal Brazeau sand. Most detrital garnet is equigranular and commonly shows dodecahedral crystal faces. Subconchoidal to conchoidal fracturing is predominant and occasionally solution etching has produced a remarkable "micro-scaly" appearance on the surface of some grains. This etching is particularly noticeable in the garnets of the Dunvegan sand (Plate III–3). Inclusions are present in all varieties and are usually of three types: opaque mineral, spherical-shaped inclusions, and fine dust.

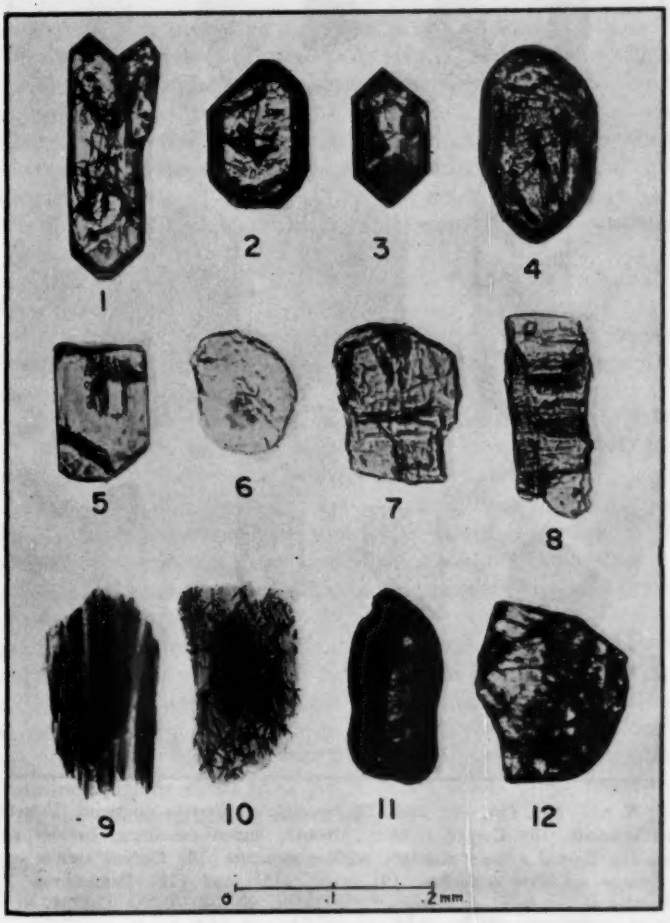

PLATE IX. Basal Paskapoo sand (Palaeocene) accessory minerals. (1) Zircon twins: inclusions and zoning. (2) Zircon euhedron: opaque and rod-shaped inclusions. (3) Zircon euhedron. (4) Hyacinth: rounded, zoned and fissured. (5) Apatite euhedron showing inclusions. (6) Rounded apatite devoid of inclusions. (7) Kyanite: cleavage. (8) Elongate kyanite, as in (7): cleavage, inclusion, and staining. (9) Augite: "hacksaw" terminations. (10) Diopside, network of acicular microlites. (11) Rounded rutile: dark, broad borders. (12) Sphene, cracked and stained.

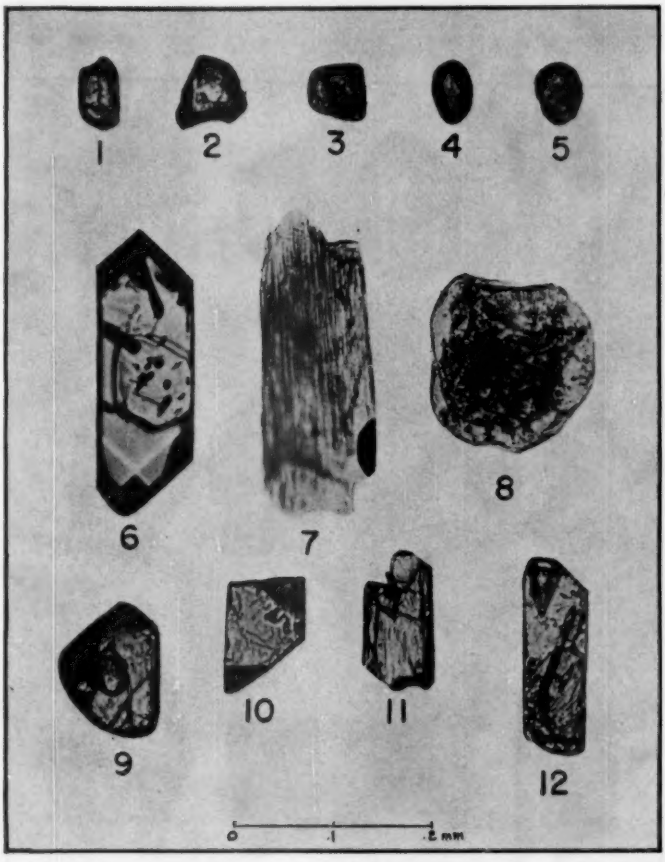

PLATE X. (1), (2), (3), (4), and (5) Precambrian Creston quartzite (Proterozoic) rounded hyacinth. (6) Coryell syenite (Albian?) zircon euhedron: cavities and inclusions. (7) Coryell syenite diallage: schiller structure. (8) Coryell syenite apatite: black, opaque spherical inclusions. (9), (10), (11), and (12) Precambrian Purcell diorite (Proterozoic) hyacinth euhedra.

Kyanite

Kyanite is an occasional constituent of some sedimentary rocks. It is more common in the basal Paskapoo sand where the typical elongate, bladed form predominates. It is colourless in most cases but very occasionally shows a pink cast (Plates V–2; IX–7, 8).

Mica

Two varieties of mica, biotite and muscovite, occur in this suite of rocks. Biotite is abundant in the intrusive rocks and is common in the sediments.

It is strongly magnetic, attracted at a current strength of 0.35 amps. to 0.45 amps. Colour varies from deep coffee-brown to pale brown and occasionally green biotite is found in the sediments. Biotite occurs in the form of flakes, occasionally pseudo-hexagonal in shape, sometimes rounded but mostly as angular fragments (Plates IV–8; III–8). Inclusions are common in the biotite grains and are, for the most part, black opaque minerals which commonly show dark halos. Muscovite is not an abundant heavy constituent of any of the samples, but it does occur regularly in the less magnetic fractions of the sedimentary rocks. It forms the usual thin, colourless flakes in perfect basal cleavage. Irregular cracks are common in the muscovite flakes (Plate III–5) which are sometimes coated with opaque dust.

Opaques

Hematite usually occurs in the moderately magnetic fractions of current strength 0.45 to 0.75 amps. It is common to abundant in all samples of both intrusives and sediments.

Ilmenite is characterized by its black colour in reflected light and its common occurrence in the hematite fractions. It is restricted mostly to the sediments.

Leucoxene varies in colour from grey to shades of yellow in reflected light. Its occurrence is not restricted to any one magnetic fraction although it is reportedly non-magnetic. Leucoxene is common in most samples.

Magnetite is particularly abundant in the intrusive rocks and occurs commonly in the sediments.

Marcasite was recognized definitely in the Coryell syenite only. The form is typical for marcasite and colour is pale yellow in reflected light.

Pyrite is a very common constituent of most non-magnetic fractions of the samples. The common crystal form here is the cube and pyritohedron. However, decay and partial alteration to the oxide frequently obscure crystal outlines. Colour varies from bright brassy yellow in the intrusives to a deep orange-yellow tarnish in the sands.

Pyroxenes

The pyroxenes are strong to moderately magnetic and attracted mostly at a current strength of 0.35 to 0.45 amps. Monoclinic pyroxenes, particularly augite, make up the greater percentage of this group. Diopside has also been recognized, usually with augite, but its occurrence is quite rare. The orthorhombic pyroxenes, hypersthene and enstatite, are restricted to the sediments where their occurrence is rare. Augite was noted in all samples with the exception of the Crowsnest tuff, Creston quartzite, Rocky Mountain sand, Cadomin conglomerate and basal Brazeau sand; colour is usually a typical grass-green with very weak pleochroism to yellowish green. The form which augite takes in these samples is the short prismatic grain or crystal. Grains with "hacksaw" terminations are common in the

sediments (Plate IX–9). Inclusions are common in augite and vary from simple opaque rounded types to elongated, black microlites. Rarely, the microlites are aligned parallel to the crystallographic *c*-axis.

Diopside is rare; it occurs with augite but is lighter green in colour. Refractive index is very close to that of aroclor (1.66). Inclusions of black acicular microlites and elongate rod-like cavities were noted in one sample. These inclusions were arranged in certain planes at angles of about 90° and 120° to each other.

Hypersthene occurs in only two of the samples: namely, the Dunvegan and the basal Brazeau sands. It has distinct pleochroism from pale green to pale pink and the index varies from 1.67 to 1.68. Fibrous to prismatic cleavage is predominant and hypersthene with a unique radiating habit occurs in the basal Brazeau sand (Plate VI–11). Very narrow and sharp dentate terminations are common in this detrital hypersthene.

Enstatite is restricted to the sediments. It is colourless but of similar form to that of hypersthene. Pleochroism is absent.

Rutile

Rutile was found in most of the sedimentary rocks but in none of the intrusives. It occurs usually in the non-magnetic fractions along with zircon and apatite. It is generally anhedral, rounded to angular and, in most cases, nearly opaque owing to its extreme refringence (Plates IV–10; VI–8; IX–11). One crystal was noted in the middle Brazeau sand which shows a well-developed pyramidal termination (Plate VII–5). Colour of rutile is deep yellowish to reddish brown with exceptionally dark borders.

Siderite

Siderite has been positively identified in the Cardium sand only. It is colourless to very pale brown with perfect rhombic cleavage.

Sphene

Sphene is common to abundant in all samples of sediments and intrusives alike. It constitutes the predominant mineral in the magnetic fractions of current strength 1.2 to 1.5 amps. and separation from the non-magnetics is nearly complete. Two varieties of sphene occur in these samples. The first is yellow to pale brown with numerous microfissures. Angular euhedra predominate (Plates II–1, 2). No preferred orientation of crystals in mounting occurs in this variety. The interference figure is in many cases pseudo-uniaxial, with very hazy brushes due to the strong dispersion. The second variety is paler yellow than the first and shows a rounded "envelope" habit (Hutton, 1952) (Plates I–8; IX–11; II–4). Microfissures and inclusions are rare. Preferred orientation in the mounting medium is apparent in this variety. The interference figure is invariably of the acute bisectrix, showing low optic angle (20°) and very strong dispersion. Complete ex-

tinction is never attained in this type; a deep blue colour results as the normal extinction position is reached.

Staurolite

Staurolite is rare and restricted in these separates. It was observed in McDougall-Segur, Solomon, middle Brazeau, and basal Paskapoo sands only. It is attracted at a current strength of 0.35 to 0.45 amps. Colour is dark brown, strongly pleochroic to yellowish brown. Conchoidal fracture is very common (Plates VII–4, 6). Inclusions are spherical to rod-shaped and may be fluid-filled.

Tourmaline

Tourmaline is a rare but persistent constituent of all the sediments. It is generally attracted in the magnetic fraction at current strength of 0.75 amps. Four varieties of tourmaline were recognized in these samples: brown, black, pink, and blue. All varieties exhibit the normal prismatic form, although in many cases extreme rounding of the grains conceals the crystallographic orientations.

Two sub-varieties of brown tourmaline are present in some of the sands: pale brown euhedra which show generally good prismatic form (Plate VIII–7); and dark brown, rounded grains (Plates VI–12; IV–11, 12). Pink tourmaline is present in the Cardium, basal Brazeau, middle Brazeau, and basal Paskapoo sands. Blue tourmaline (indicolite) was noted in the Solomon and basal Brazeau sands. Black acicular inclusions occurring in some of the brown tourmaline are thought to be rutile, but positive identification was not possible.

Zircon

Zircon is abundant and widespread in all samples examined in the study with the exception of the Crowsnest tuff. Most zircon occurs in the non-magnetic fractions of the separates, generally between the grade sizes 100 and 200 mesh. Two varieties are present: colourless to pale yellow, generally euhedral zircon; and pale pink to purple, rounded "hyacinth" zircon. The colourless variety is by far the more common of the two and comprises 95 per cent of the zircon concentrates. The typical form which this zircon takes is the square prism, vertically elongated and terminated by pyramids. In general, the pyramids are obscured by rounding, but in most of these intrusive rocks perfect crystal form is the rule (Fig. 3). Colourless zircons of the Rocky Mountain sand and Cadomin conglomerate are well rounded, in contrast to those of the Upper Cretaceous sands (Fig. 4). This rounding indicates successive cycles of erosion.

Rod-shaped apatite (?) inclusions and spherical fluid-filled cavities are very abundant in the colourless zircon. In many instances these inclusions are aligned parallel to the *c*-axis, but just as frequently there is no particular orientation (Plate I–1). Black opaque mineral inclusions are also present

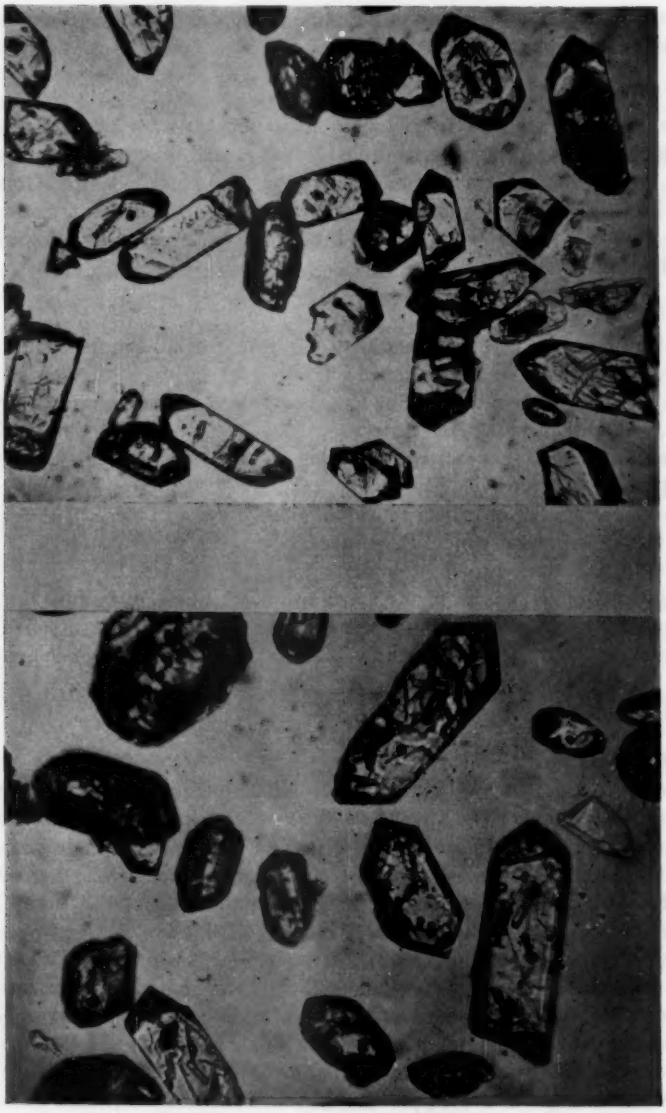

FIGURE 3.—Euhedral zircons from quartz monzonite, Boulder batholith, near Helena, Montana (lower); clear zircons from the Coryell syenite, a phase of the Nelson batholith, near Rossland, B.C. (upper).

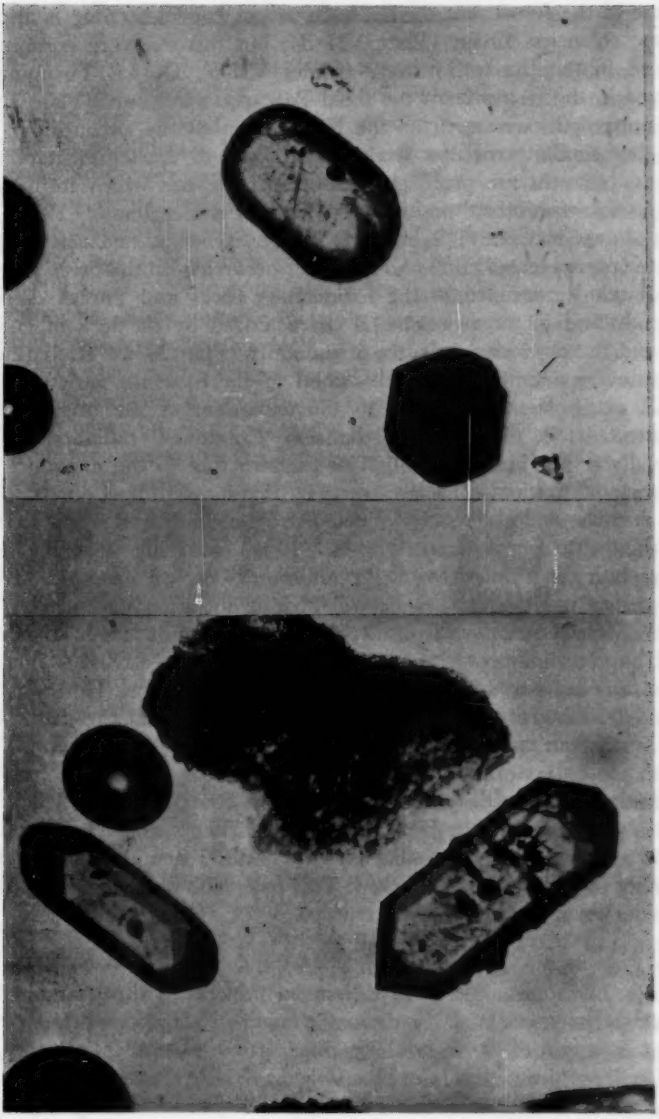

FIGURE 4.—Rounded zircon from Cadomin conglomerate (Lower Cretaceous) contrasts sharply with the euhedral zircons from the Dunvegan sandstone (Upper Cretaceous).

in some of the forms, but their identity is not known. Zoning is apparent in some colourless zircon (Plate VII–3), but this structure is more pronounced in the hyacinth variety (Plates VII–2; IX–4). Twinning was observed in the zircon from the basal Paskapoo sand only (Plate IX–1). True outgrowths were seen on the Nelson granodiorite zircon only (Plate I–7), but similar structures were rarely noted in the sedimentary rocks. These outgrowths are protuberances of variable size which form on the parent euhedron in any position (Poldervaart & Eckelmann, 1955). The zircon shown in Plate I–7 has two such outgrowths, one extending out from the parent termination and the other occurring on the prism face.

Hyacinth is restricted to the sedimentary rocks and Purcell diorite of this study and in the sediments is characterized by the lack of euhedral form and the pronounced degree of rounding (Plate X–4). Radiating and anastomosing microfissures are common in the hyacinth variety. Hutton (1950) attributes these cracks to the expansion of the original zircon structure owing to radiation damage. Continued radiation damage eventually results in disintegration of the structure to the metamict state. This metamictization is accompanied by density, hardness and refractive index decrease and also change of colour from colourless to yellow to brown and, finally, to purple tints. Tomita (1954) concludes that the age of the hyacinth variety of zircon is Precambrian or early Palaeozoic. Much of the fissuring radiates from a central opaque inclusion or nucleus (Plate VII–2). Zonary structure is most common in hyacinth zircon and is produced by very fine concentric banding (Plates VII–3; IX–4). Inclusions are for the most part similar to those in the colourless type. However, frosting and cracking of the surface of the hyacinth conceal the inclusions in many instances.

With the exception of the hyacinth variety none of the zircons possess sufficiently distinctive features to separate one from the other. Pale yellow euhedra were noted in the Dunvegan and Cardium sands. These, however, are not common enough to indicate clearly a different source, although this possibility should not be overlooked. This pale yellow variety is identical to the colourless zircon in all other respects.

Zoisite

Zoisite, like tourmaline, is a widespread mineral in these samples. It is moderately magnetic and occurs in the magnetic fractions attracted at a current strength of 0.45 to 0.75 amps. It is generally colourless, but occasionally grains with a faint blue tinge have been observed. Inclusions of hornblende microlites are seen rarely in the zoisite of these samples and most inclusions are spherical opaque masses.

Other minerals have been recognized in these samples, but their occurrence is so rare they have not been treated under a heading. They include: allanite, brookite, clinozoisite, corundum, and monazite.

Provenance

Such minerals as rounded hyacinth zircon (Precambrian), rutile and tourmaline in the heavy fractions, together with chert and orthoquartzite grains in the "light" mineral fractions, indicate a pre-existing sedimentary source for these minerals. Kyanite, garnet, staurolite, epidote, zoisite and chlorite are indicative of an original metamorphic source. Apatite, euhedral zircon, sphene, pink tourmaline, hypersthene, hornblende, and augite suggest an igneous source. The constituents of the Upper Cretaceous sediments were derived primarily from a pre-existing sedimentary source; however, igneous and metamorphic rocks also made a significant contribution to these sediments. Many unstable minerals such as augite, staurolite, zoisite, hornblende and hypersthene which occur in the late Lower Cretaceous, Upper Cretaceous, and Tertiary rocks, suggest that chemical weathering was slight and deposition and burial of the sediments was rapid. In view of the inferred proximity to the source, it appears probable that sediments of the Lower Cretaceous McDougall-Segur conglomerate and the Upper Cretaceous and Tertiary, Dunvegan, Cardium, Solomon, Brazeau and Paskapoo sands were derived from the area to the west of the Alberta foothills region. The mineralogy of the Permo-Carboniferous Rocky Mountain sand and the Lower Cretaceous Cadomin conglomerate is strongly suggestive of a pre-existing sedimentary source which, in all probability, is also to the west. However, the paucity of first cycle igneous and metamorphic type minerals in this conglomerate suggests that the igneous source of the Upper Cretaceous constituents was not a contributor to the Rocky Mountain and Cadomin depositional sites. In other words, Mesozoic British Columbia batholiths were unroofed in the interval between Cadomin (Neocomian) and McDougall-Segur (Albian) time. Warren (1951) has suggested that the first evidence of the unroofing is to be seen in the McDougall-Segur conglomerate of the Blairmore. We found igneous pebbles from this conglomerate to contain a heavy mineral suite identical with that of the Nelson batholith. The conclusion of Smith and Stevenson (1955) that the McDougall-Segur igneous pebbles could have come from the Purcell intrusives is quite untenable. There are no hyacinths, which are typical of the Purcell diorites (Plate X, 9–12), in the McDougall-Segur igneous pebbles.

In view of the 105 m.y. (Albian) age determined for the Nelson batholith, it is probable that this particular pluton was a major contributor to the late Lower and Upper Cretaceous depositional site. Other intrusives of similar age, possibly the Cassiar and Omineca batholiths of northeastern British Columbia, contributed igneous constituents to the Upper Cretaceous and Tertiary sediments of the northern Alberta foothills.

Our conclusions are essentially those reached by Warren (1951) using palaeontology as the practical basis of geochronology, in his presidential

address to the Royal Society, "The Rocky Mountain Geosyncline in Canada." Perhaps the methods of determining time by physical methods have come of age.

Acknowledgments

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME L : SERIES III : JUNE, 1956
SECTION FOUR

Tectonics of the Maritime Area*

H. L. CAMERON
Presented by F. J. ALCOCK, F.R.S.C.

Introduction

NOVA Scotia is one of the most completely geologically mapped provinces in Canada. Three-quarters of this mapping was done before 1920 at 1″ = 1 mile and the remainder at 1″ = 3.95 miles. Since then, approximately one-half has been redone to modern standards and published on new accurate base maps. All serious errors of stratigraphy have been corrected by palaeontological studies and the general areal geology republished by the Geological Survey of Canada in the new (1949) geological map of the Maritime Provinces. This map also gives the corrected geology of New Brunswick. The new geological map of Canada (1955) gives a generalized version of the geology of the Maritime Provinces, Quebec, and Newfoundland.

During the last ten years a great deal of geophysical work has been done in Nova Scotia and the adjacent parts of New Brunswick, particularly in the Moncton-Stoney Creek area. A synthesis of the New Brunswick material has been published by W. A. Gussow (1953).

The writer has spent considerable time during the past fifteen years compiling information on the structural geology of Nova Scotia. By combining published maps, air-photo interpretation, and geophysical data, particularly airborne magnetometer and gravity surveys, the assembled material has been cross-checked and additions and reasonable extrapolations made. The result is the tectonic and geological map which is presented here (Figure 1). It will be referred to again later.

The new structural and geological map of Newfoundland, the tectonic map of Canada, the tectonic map of the United States, and the extensive subsea geophysical investigations of Ewing and others of the submerged Atlantic coastal plain, the Gulf of Maine, the Grand Banks and the continental rise, complete the data used in this tectonic study of the Maritime area.

General Geology

The area to be discussed is bounded on the north and west by the Canadian Shield and early Palaeozoic rocks, the general boundary being a thrust fault of unknown but probably large displacement. In the north and east,

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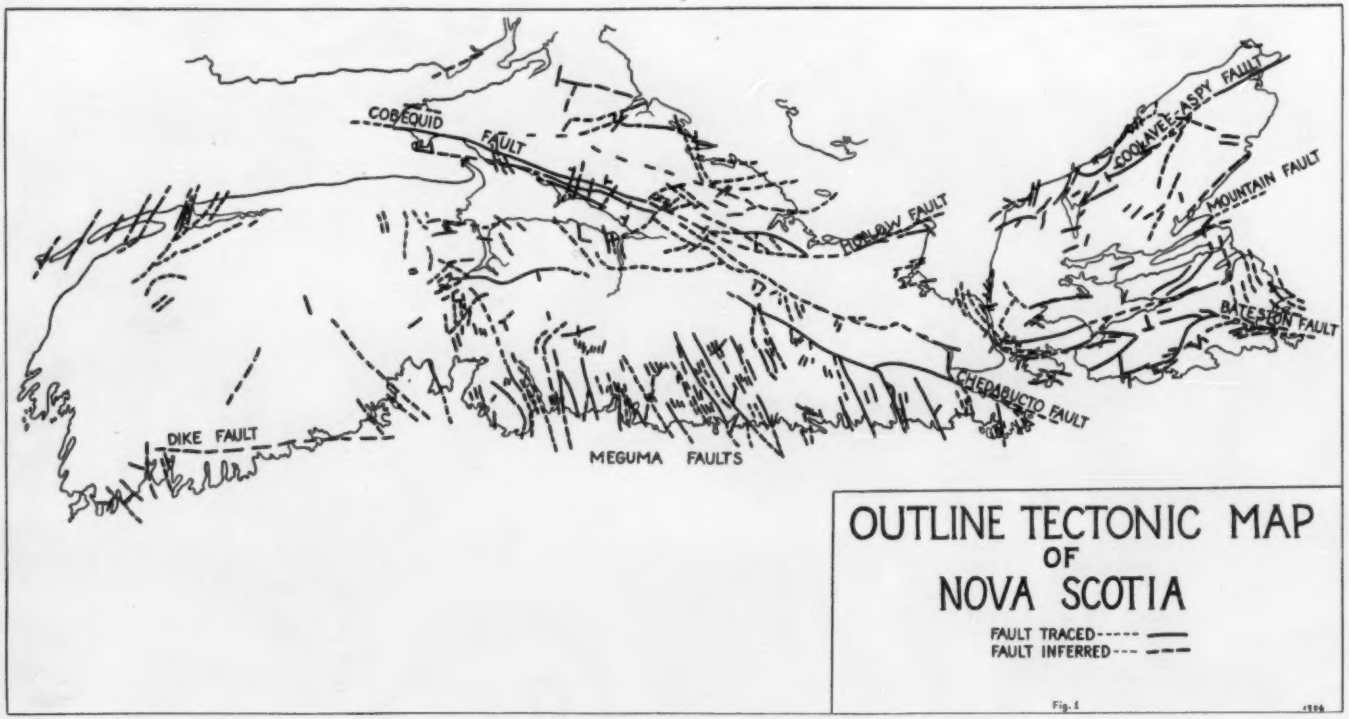
COBEQUID
FAULT
COBEQUID-CHEDABUCTO FAULT
MOUNTAIN FAULT
HOLLOW FAULT
BATESTON FAULT
CHEDABUCTO FAULT
DIKE FAULT
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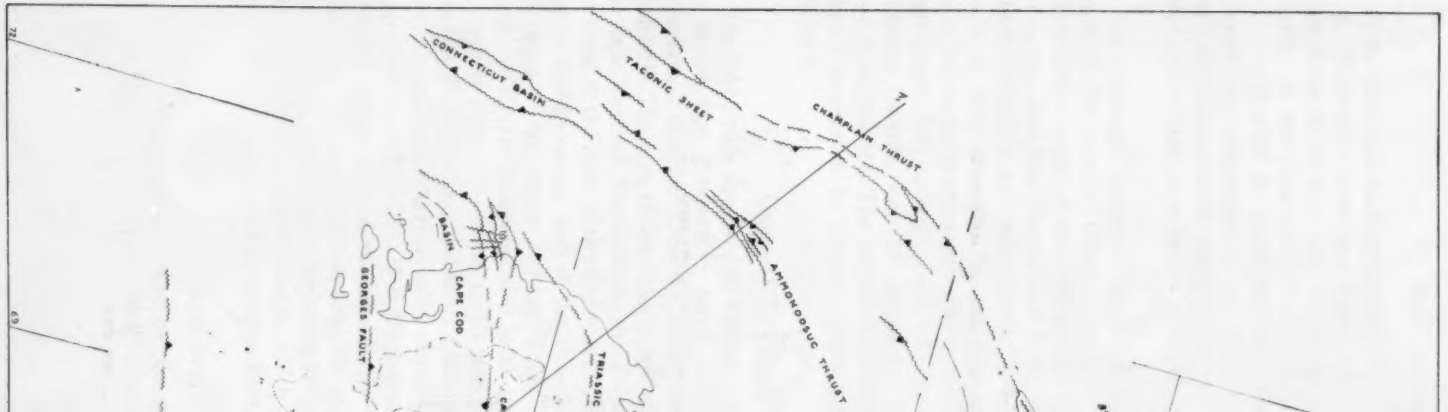
OUTLINE TECTONIC MAP
OF
NOVA SCOTIA
FAULT TRACED-----
FAULT INFERRED---
Fig. 1

FIGURE 1


72
69
CONNECTICUT BASIN
TACONIC SHEET
CHAMPLAIN THRUST
BASIN
CAPE COD
GEORGES FAULT
AMMONOOSUC THRUST
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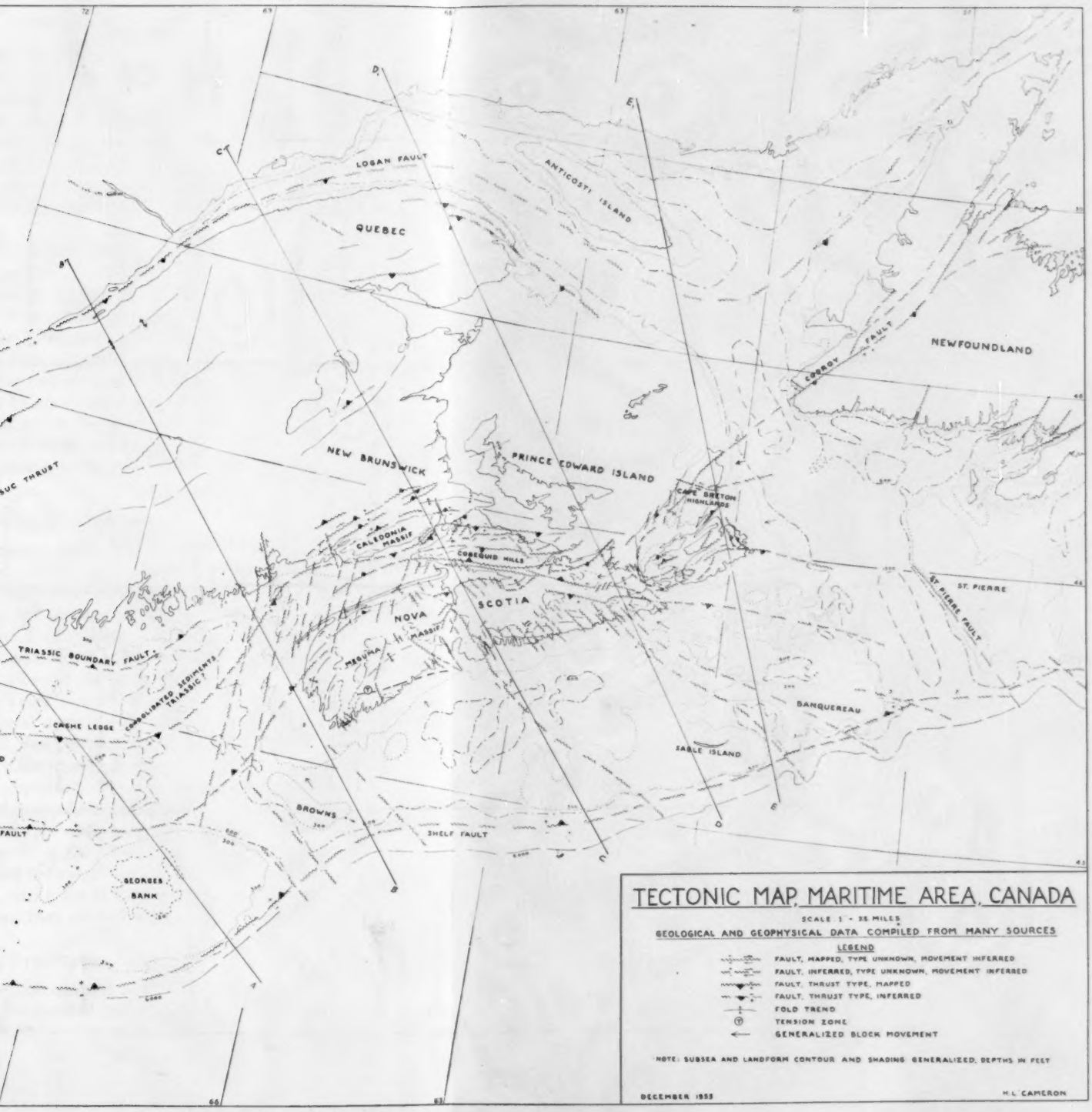
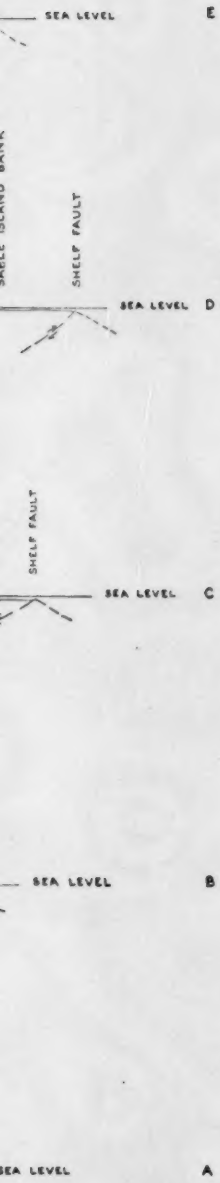


FIGURE 2.—Tectonic map, Maritime area, Canada.

CROSS SECTIONS OF THE APPALACHIAN GEOSYNCLINE - FROM WEST TO EAST

FIGURE 3.—Cross-sections of the Appalachian geosyncline from west to east.



as in the west, this fault apparently diverges from near the overlap contact of the Palaeozoic rocks and leaves large areas of low-dipping Palaeozoic strata between the fault and the shield. The boundary on the southeast is the edge of the Continental Shelf, which is inferred to be a thrust fault similar to that on the north and west. These two major faults are believed to mark the boundaries of the Appalachian geosyncline. Both marginal faults dip in towards the centre of the geosyncline and form a type structure which is repeated on a smaller scale throughout the region (Figures 2 and 3).

The structural trends of the Palaeozoic rocks conform to the general course of the marginal thrust faults. The successive fold axes of the Shickshock-Gaspé ranges in the west and north, and the Meguma series in the south, are examples. The cores of these folded zones have been intruded by granite batholiths and other igneous rocks ranging down to ultrabasic. The origin of these intrusions has not been discussed in the literature, but in Nova Scotia the granites of the Meguma series massif show many traces of sedimentary fold structures and with their practically undisturbed granite sediment contacts, they are considered to be granitized sediments rather than true granites. The consolidated rocks within the area range in age from Precambrian to Triassic. Their general relationships are shown in Figure 4.

General Structural Geology

The fold trends are given in Figures 2 and 4. The general conclusion can be drawn that compressive forces acting approximately normal to the geosynclinal margins threw the accumulated sediments into folds trending as shown. The ages of the folding episodes are known appoximately from the rocks involved. For example, the Taconic folding, followed by thrusting, occurred at the close of the Ordovician; the Shickshock and Meguma folding in mid-Devonian and at the close of the Devonian, followed by, or accompanied by, thrust faulting. There is considerable evidence in Nova Scotia and New Brunswick that local anticlinal or positive areas of early Palaeozoic rocks (Cambrian to Silurian) were elevated in late Ordovician and late Devonian time and formed the sources of sediments for most of the Mississippian and Pennsylvanian deposition. Most of the later deposition took place in local basins or epieugeosynclines with the whole cycle being repeated several times as the local basins were compressed and the margins overthrust. This is a concrete example of the "welt" theory of geosynclinal development, where early deposited sediments are locally folded and uplifted to form marginal highlands, which are in turn eroded to supply sediments to local basins or epieugeosynclines on both sides of the folded zone.

Type Structure

The type structure is a syncline, compressed until overthrusting occurs on both sides. As an example, the Cumberland epieugeosyncline is described.

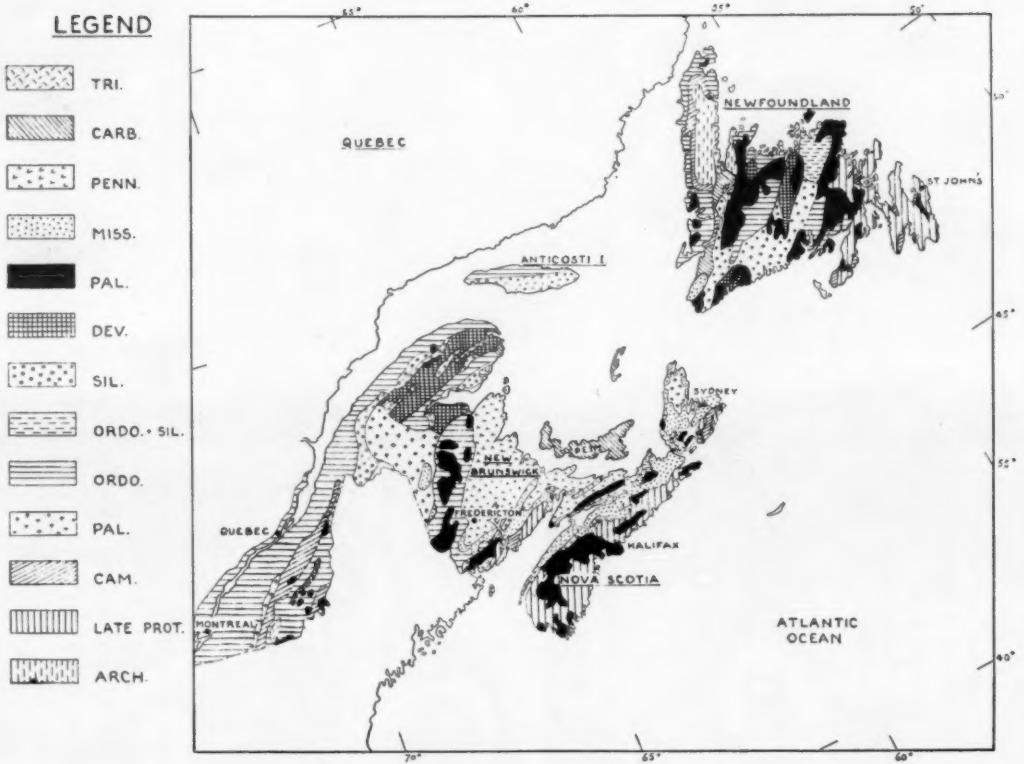


FIGURE 4.—General geology of the Maritimes and eastern Canada.

This local basin is located between the Caledonian massif of New Brunswick and the Cobequid Hills of Nova Scotia. The Caledonian massif comprises metamorphosed rocks of possible Precambrian, but more likely of early Palaeozoic age with igneous intrusions. The Cobequid Hills include Ordovician and Silurian sediments with intrusive granite, probably Devonian. The basin proper contains a great thickness of Carboniferous sediments ranging from Mississippian (Horton) to Middle Pennsylvanian (Cumberland). The field evidence indicates that deposition began in early Mississippian and probably continued until late Mississippian (Canso) time. The basin was then compressed and the Cobequid positive area was folded into at least two anticlines, which were eventually overthrust to the south. A similar double or triple fold developed in the New Horton area where the folds were tightly compressed and finally overthrust against the Caledonian massif. Deposition of Lower Pennsylvanian (Riversdale) strata began on both sides of the Cobequid uplift and continued until the close of that period, when renewed compression resulted in uplift along the marginal faults. This periodic uplift continued throughout the Pennsylvanian and each group of strata is based on heavy boulder conglomerates which undoubtedly formed at the base of the fault scarps. There is evidence of the continuing compression of the Pennsylvanian (Riversdale), Middle Pennsylvanian (Cumberland), and Upper Pennsylvanian (Pictou) groups. The general concept is shown in the cross-section of the basin (Figure 5).

One final point of interest in the general tectonic framework is the long, narrow graben located just south of the Cobequid fault. This apparent anomaly is readily explained if the effects of compression between the Caledonian massif and the Cobequid Hills are considered. Such compression would result in an eastward movement of the block between them with a northward movement along the "ramp" of the Hollow Fault and thus set up tension along the south margin (Figure 2.).

Summary

The general fold and fault pattern have been outlined. Synclinal structures, bounded by inward-dipping thrust faults are shown to occur throughout the general area believed to represent the Appalachian geosyncline. They are considered to be epieugeosynclines bounded by positive uplifts, or "welts," which formed periodically and in various locations during the development of the Appalachian geosyncline. This is believed to have consisted of the development of local geosynclines or eugeosynclines in which early Palaeozoic sediments accumulated. These local geosynclines were compressed and developed folds and marginal overthrusts and uplifts, the whole forming a highland source of sediments for middle and late Palaeozoic sediments in eugeosynclines. The same cycle was repeated and the present state of the outcrop pattern of the Appalachian geosyncline can be explained on the basis of this hypothesis. It follows that the development

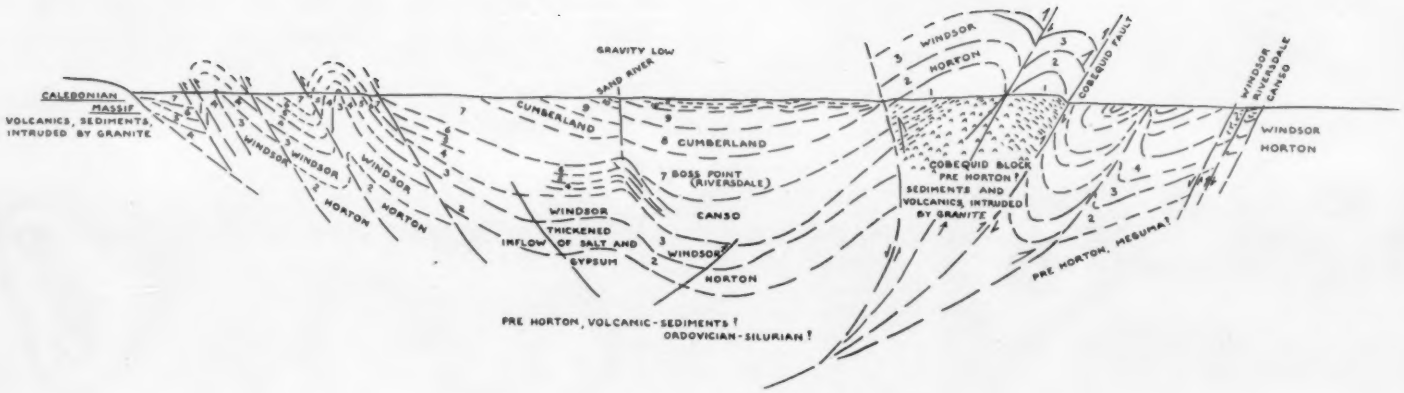


FIGURE 5.—Cross-section of the Cumberland epieugeosyncline.

of a major geosyncline, such as the Appalachian, is a long-continued and complex series of cycles of deposition, collapse, uplift and erosion. Such a concept does not require marginal highlands to provide sediments, and in fact requires little else than continued compression operating in the zone between the continental craton and the oceanic block.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
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SECTION FOUR

Chemical Compositions of the Grenville and the Southern Part of the Timiskaming-Keewatin Subprovince in Quebec

F. FITZ OSBORNE, F.R.S.C.

ABSTRACT

The ratios of the normative feldspars of the plutonic rocks of Abitibi and of the Grenville subprovince are quite different. However, taking account of other rocks, the average compositions tend to be similar. The region with northeast strikes, southeast of Abitibi, was the locus from which albitic magmas came.

Introduction

In Professional Paper 127 of the United States Geological Survey, F. W. Clarke and H. S. Washington discussed the analyses available from eastern Canada for use in arriving at an average composition of this part of the earth's crust. In 1924, they compiled 99 analyses from Quebec and Ontario, suitable for incorporation in the average, but they state that the relatively numerous analyses from Sudbury, Cobalt, Rainy Lake and of the alkaline rocks of the Haliburton and Bancroft area, and the Monteregian intrusive rocks, result in a misleading average.

Washington, in Professional Paper 14, which was published in 1917, compiled the analyses published up to 1914. He included 58 analyses from Quebec, but 34 of these are from the alkaline Monteregian province. He did not include some analyses of Precambrian rocks because of incompleteness, alteration, or the possibility that they were paragneisses. Washington used only igneous rocks in arriving at his average analysis.

Recently, C. Faessler has compiled for the Quebec Department of Mines the analyses of rocks and minerals from Quebec. Excluding technical analyses for ores but including analyses of minerals, rocks, clays, and mineral waters, about 3,000 analyses are listed in the compilation, many of which are unpublished, having been made in the laboratories of the Quebec Department of Mines. Another source of analytical data that is commonly overlooked by geologists is the reports of soil surveys carried out for the Departments of Agriculture. To a geologist, the analyses are incomplete, but they commonly have a determination of K_2O which may be used to supplement some analyses of clays and silts, many of which have combined K_2O and Na_2O.

An examination of the geographical distribution of the analyses shows that some rocks from the Keewatin-Timiskaming subprovince south of latitude 50° are well represented, and that analyses of the rocks from a strip

of the Grenville subprovince are numerous enough to give some data. Unfortunately the northwest side of the Grenville subprovince is poorly represented.

I intend to discuss some of the differences and similarities in the two structural regions. It is not my intention to arrive at average compositions, but rather to discuss the recipes that might be used and the characteristics of the ingredients that enter the recipes.

It is certain that the average composition, no matter how it be arrived at, will have approximately two-thirds feldspar equivalent, with quartz forming at least a third of the remainder. Since feldspars are dominant, they obviously must receive special consideration. I have computed the composition of the normative feldspars in terms of the ratios of Or: Ab: An in mols and plotted the results for different groups of rocks on triangular diagrams. Mol percentages have been used for they keep the ratios on the plagioclase join in conformity with the customary designations. They do not differ much from the ratios in weight percentages. Many of the rocks are not markedly abnormative, and for these norm and mode are, therefore, similar.

This similarity allows the ratio of potassic feldspar to plagioclase to be inferred from thin sections. Staining with sodium cobaltinitrite and Rosiwal analyses have proved serviceable in establishing the character of some rocks for which analyses are not available. The field criterion that the potassic feldspars are pink whereas the plagioclase feldspars are grey, is so uncertain that it is worthless. Examples have been encountered in the laboratory in which the colours are the reverse of that normally considered the rule. Furthermore the plagioclase of many rocks does not show a recognizable twinning. It has been found possible to apply the staining technique to chips in the field. The chips are covered with a paste of NH_4F and dilute HCl and are left overnight in a plastic soap dish. The lightly washed specimen is treated with concentrated sodium cobaltinitrite. Unfortunately plagioclase with fine muscovite also stains, but the method is useful for rocks with glassy feldspar.

Keewatin Timiskaming Subprovince

Most of the analyses of igneous rocks are from a strip about 40 miles wide extending from longitude 77° to the Ontario boundary and between latitudes 48° and 49°; in turn, most of these rocks are from stocks or small batholiths near which gold mineralization occurs. These masses are apparently younger than the principal folding, that is, post-kinematic. As will be seen in the diagrams (Figures 1 and 3), the rocks are largely tronjhemitic varieties, generally characterized by abundant modal albite or oligoclase. This is shown by the cluster of points near the albite vertex of the triangular diagram (Figure 3). Nevertheless, the oxides of the analyses do not fall on lines on a normal oxide variation diagram. I presented in 1937 a diagram of the rocks of the Quebec-Ontario gold belt. The diagram, based on about

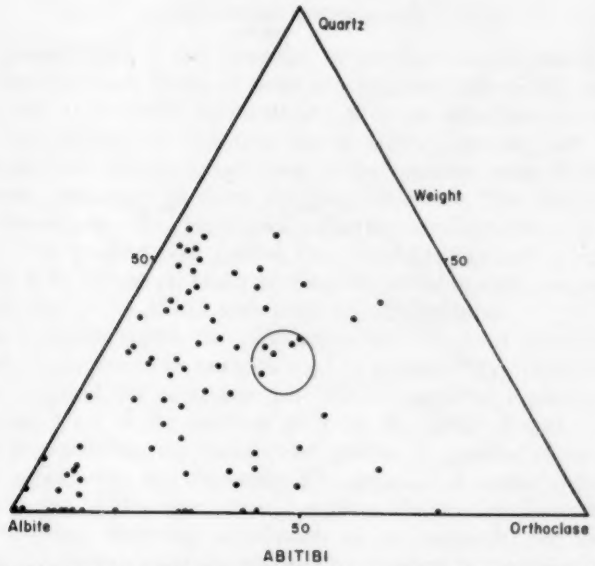

FIGURE 1.—Analyses of rocks from Abitibi region: Ratio of albite, potassic feldspar, and quartz of norm. Large circle area of "normal" granite.

60 analyses, fitted the then available data. With the new analyses, however, scattering becomes extreme, and smooth curves can only be got by considering analyses from one or two masses at a time. The diversities may be seen by comparing the trends on a triangular diagram (Figure 2), using the ratios by weight Na_2O and K_2O, MgO, and total iron calculated as ferrous iron. This diagram has the advantage that several trends may be compared. On the other hand it does not give the ratio of albite to potassic feldspar and neglects anorthite. Different trends in crystallization-differentiation are a possible explanation for this, but effects of incorporation of material or more probably of metasomatism cannot be ruled out.

Figure 1 shows the ratios by weight of normative albite, orthoclase, and quartz. The large circle shows the centre of the region occupied by "normal granites." The number of analyses falling outside this circle is surprising. The analyses falling inside the circle are, with one exception, from the Lamotte-Lacorne mass. No doubt the students of mineral deposits can draw some conclusion from this.

The foregoing group of rocks represents only a part of the region. In the country between this belt and Chibougamau many plutonic rocks crop out, but no analysis is available. It is my impression, however, that many of the rocks are less albitic than those shown on the diagram. Inspection of thin sections suggests the albite component of the feldspars is about equal to the potassic feldspar. Oligoclase is the common plagioclase.

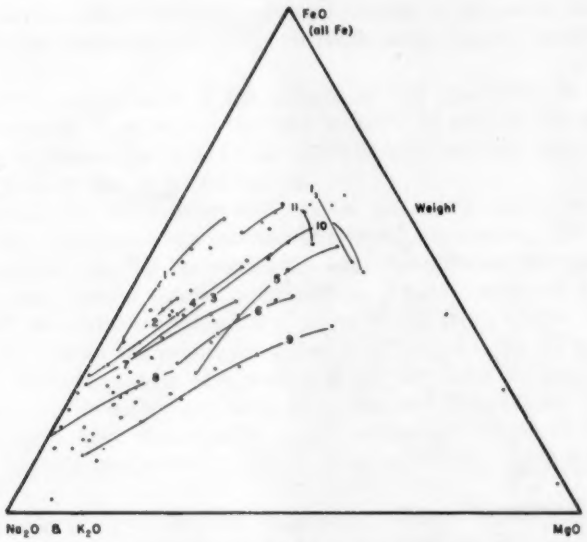

FIGURE 2.—Diagram of analyses of Abitibi intrusive rocks. (1) Pascalis-Tiblemont; (2) Eldona; (3) Palmarolle; (4) Taschereau; (5) MacDonald Mine; (6) Lamaque Mine; (7) Duvernay; (8) Lamotte-Lacorne; (9) Chibougamau-Opemiska; (10) Bourlamaque-Siscoe; (11) Diorites—Malartic.

Another region for which analyses have not been made is in the zone lying southeast of the Keewatin-Timiskaming subprovince. Geologists of the Quebec Department of Mines have been able to trace the bands of the rocks of the greenstone type eastward along their trends into a belt of high grade metamorphism. A northeast striking structure is superimposed on the east striking structures. In the belt of deformation the intrusive rocks with abundant albite component tend to be in masses of conformable, that is synkinematic, habit and many of them are gneissic. Some post-kinematic intrusive rocks, most of which are syenite or quartz syenite, occur. A certain number of these have potassic feldspar in excess of plagioclase, but others are rich in albite.

The exact width of the belt with albitic rocks is not known. However, it is probably as wide as the Mattawa gravity low, determined by Garland (1950), which extends more than 26 miles down the Ottawa River from Mattawa. Barlow (1899) has given some analyses of "granitite" from Témiscamingue Lake and Kipawa Lake. Of the six analyses, three show Na_2O dominant over K_2O, and two at least are probably paragneisses. Other analyses are from a report by Gillies (1952), but considerable reliance must be placed on the modes to supplement the analyses (Wahl and Osborne, 1950).

Grenville Subprovince

The igneous rocks of the Grenville subprovince are abundant and of diverse characteristics. Many of them are intimately associated with paragneisses, both as *lit-par-lit* injections and as larger stratiform or lenticular bodies. The conformable injections are commonly gneissic, and they are synkinematic and pre-kinematic. Some of the intrusive rocks of this group are potassic, but many of them are plagioclase-rich. The single analysis that lies towards the albite vertex of the diagram for Grenville rocks (Figure 3) is of a fine-grained pink granite from near Quebec and is apparently one of the older intrusives. Many of the older intrusive rocks are grey, however, and contain An 15–25 with some potassic feldspar.

In the Grenville region the anorthosites form domical massifs and are sufficiently distinctive to be easily outlined in mapping. The cluster of points near the centre of the albite-anorthite join on Figure 3 represents mostly anorthosites. Most of the analyses are from the Morin massif.

Green pyroxene-bearing rocks, from gabbro to granite, occur in force near the anorthosites and elsewhere. The presence of similar pyroxenes in these rocks and in the anorthosites has given rise to a tendency to regard the whole group including anorthosites as co-magmatic, the anorthosite being the oldest member of the group. The evidence of co-magmatic origin is not unequivocal, although the rocks are closely related in time. The green rocks show some similarity to the charnockite sequence. In Figure 3, the analyses of charnockitic rocks as compiled by Quensel (1951) are indicated by triangles, and the similarity of the field occupied by the Quebec rocks to that of the charnockitic rocks is obvious. Nevertheless, all the Grenville rocks, although falling in the charnockitic field, do not have a charnockitic mode. Many have hornblende alone or associated with pyroxenes. Some have considerable biotite. Quensel's discussion of the charnockitic rocks shows the difficulties with the precise definition for charnockitic. The mineralogy of the rocks is probably a result of the conditions in the environment of consolidation and it is improbable that the conditions were identical from locality to locality.

Large outcrops of post-kinematic granite in Quebec have compositions near the centre of the albite-orthoclase join of Figure 3. These granites with some syenitic facies are commonly coarse-grained pink and have biotite.

The Chatham-Grenville and Rigaud stocks are the youngest Precambrian intrusive rocks in the Laurentian area. They are known to cut the diabase dykes The rocks, which are mildly alkaline, are from syentites to granites, and analyses by Leroy and Bain give the ratios enclosed by the dashed line on Figure 3. Their similarities to some of the Abitibi rocks are obvious. Some alkaline and even feldspathoidal rocks from south of Mont Laurier may be related to them, but the relationships of the rocks south of Mont Laurier to the diabase dykes is not known.

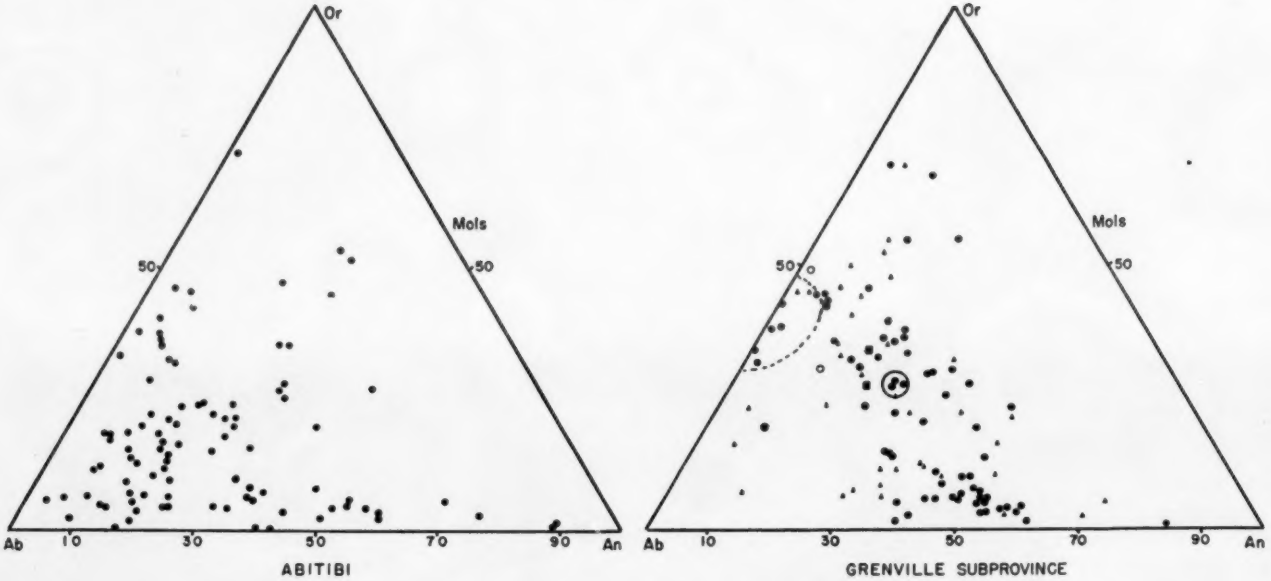

FIGURE 3.—Ratio of normative Ab, An, and Or. Abitibi analyses left. Grenville analyses right. Solid circles—Grenville igneous rocks. Small open circles—Wapussakatoo mountains. Squares—Buddington's averages of Adirondack igneous rocks. Large circle—average of seven analyses of clays from Fort Coulonge. Triangles—charnockitic rocks according to Quensel.

Buddington (1939) has given two weighted average compositions of the Adirondack rocks. One average includes the granites, the other does not (see Table I). The average of seven complete analyses of clays and silts from near Fort Coulonge reduced to an anhydrous basis is shown for comparison. It is improbable that these clays were derived from an area with

TABLE I

AVERAGES OF ADIRONDACK IGNEOUS ROCKS AND AN AVERAGE CLAY

	I	II	III
SiO_2	62.2	65.5	61.4
TiO_2	.7	.6	1.1
Al_2O_3	18.1	16.5	16.1
Fe_2O_3	1.3	1.5	2.8
FeO	3.0	2.6	2.8
MgO	1.1	.8	3.8
CaO	4.7	3.4	3.8
Na_2O	4.4	4.0	3.2
K_2O	3.9	4.6	3.3
H_2O	.4	.4	
P_2O_5	.2	.2	.3
BaO			.4
MnO			.1
SO_3			nil

I Average of igneous rocks of the Adirondacks excluding granite, Buddington (1939, p. 235).

II Average of igneous rocks of the Adirondacks including granite, Buddington (1939, p. 235).

III Average of seven complete analyses of clay from Fort Coulonge, calculated to 100 per cent without water and CO_2.

abundant Grenville series. On the other hand, contamination by Palaeozoic rocks is possible. If this is the case the average should be moved towards the albite vertex by some unknown amount. This would bring the analysis closer to Buddington's average for the Adirondack rocks without granite.

EFFECT OF NON-PLUTONIC ROCKS

The differences, in so far as available analyses indicate them, between the plutonic rocks of Abitibi and the Grenville subprovince are obvious, but other rocks occur in both regions and must be considered in arriving at an average composition. The Keewatin greenstones together with meta-sedimentary rocks are dominant in Abitibi. R. Bienvenu (1955) has studied the Abitibi greenstone and arrived at the conclusion that many of them were normal plateau types of volcanic rocks. The analyses are of much altered specimens, commonly silicified and carbonated. Specimens near mineral veins have much sericite and hence on calculation show much Or. The analyses from Quebec are shown in Figure 4, but it is probable that a composition near the average andesite would better represent the greenstone.

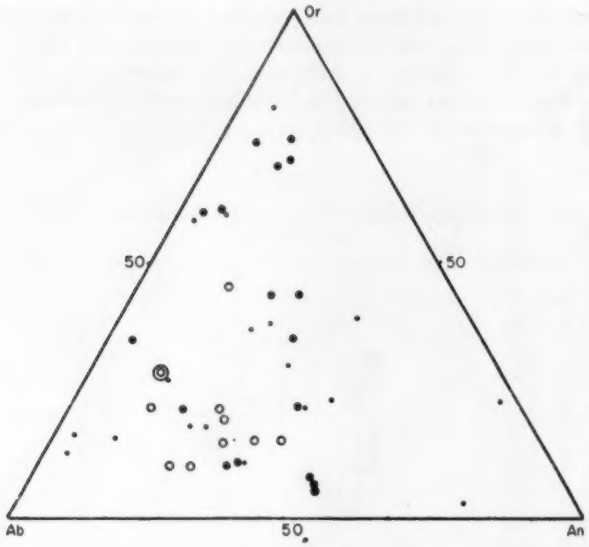

FIGURE 4.—Ratio of normative feldspars in "paragneisses." Small solid circles—Keewatin volcanics" neglecting calcite of norm. Large solid circles—Grenville paragneisses. Large open circles—analyses from region between Abitibi and Grenville subprovince. Concentric circles—Adirondack paragneiss.

Only three analyses of meta-sedimentary rocks from Abitibi have been made and all are of altered rocks. Probably some of the analyses of "volcanics" are of basic meta-sedimentary rocks. The dirty sandstone rocks have about 65 to 75 per cent SiO_2, soda in excess of potash, and an alumina excess of less than 10 per cent over that required for feldspar (Boisvert, 1954). Such rocks yield a quartzose gneiss on metamorphism. No analysis of the finer grained clastic rocks of Abitibi is available. The rocks have the characteristics of soda shales and on metamorphism yield rocks that are modally identical to those of the Grenville region, that is they are close to the 60 per cent albite of Figure 4. Some of these rocks have enough alumina to give staurolite and andalusite on metamorphism.

The Grenville series is commonly considered to have limestone, quartzite, and paragneisses, particularly gneisses with sillimanite and garnet. As I suggested in Section IV's symposium on Grenville rocks, these lithologies do not have a great outcrop area, and their analyses are not very significant in arriving at an average. Most of the analyses of the sillimanite gneisses are within the 50 per cent Or line on the triangular diagram (Figure 4). Most of these rocks are intimately associated with limestone and quartzite and, as suggested by Adams (1895), their distinctive composition is probably original.

Paragneisses with plagioclase and hornblende or biotite, or both, are

more abundant than the sillimanite-bearing gneisses. Areal mapping is not far enough advanced to determine the proportion that they contribute to an average composition, although it is almost certainly one-third and perhaps one-half if the material in injection and composite gneisses is considered.

The association of hornblende and intermediate plagioclase (amphibolite) is peculiarly stable in all parts of the Grenville subprovince. Some rocks of this composition are derived from gabbro, some from basic dykes, some from basic volcanics, and some from sedimentary rocks. In certain localities a small amount of garnet occurs, and in others hypersthene and augite are present, suggesting a metamorphism verging on the granulite grade. A consistent feature of the mode is about 5 per cent quartz.

The paragneisses, in which biotite takes the place of hornblende, show less calcic plagioclase and, at some localities, an increase of potassic feldspar and quartz with increasing biotite. Table II shows modes of some rocks

TABLE II

MODES OF PARAGNEISSES FROM NEAR HULL

Each is average of Rosiwal analyses of several thin sections. Volume per cent. (Sabourin, 1955, p. 35)

	I	II	III
Hornblende	65.1	39.2	nil
Biotite	nil	8.8	26.6
Plagioclase	(An_{30}) 26.4	(An_{25}) 43.1	(An_{12}) 55.9
Quartz	4.4	3.1	14.8
Accessory minerals	4.0	5.8	2.6

from a district near Hull. Comparable modal analyses have been made from many districts. In some the plagioclase is consistently more anorthitic, but they all show the same differences related to the characteristics of the mafic minerals. The analyses of the less hornblendic rocks of the group from east of Shawinigan Falls are along the 60 per cent Ab line of Figure 4. It is to be noted that QbA, which is considered by Engel and Engel (1953) to be the least altered paragneiss in the Adirondacks, falls on the same line. Engel and Engel go to considerable length in discussing the origin of a rock of the composition of QbA. It does not contribute to a solution of the problem to point out that this is a leptite composition. However, comparable analyses can be found in sedimentary rocks from eugeosynclines such as the Appalachian region in Quebec or miogeosynclinal rocks like the Beltian of British Columbia.

The foregoing discussion shows that, with the non-plutonic rocks included, the average of Abitibi rocks would be displaced towards the field occupied by the Grenville rocks. If as inferred above some of the igneous rocks of the Abitibi which are not stocks are more potassic, the average would be displaced towards the K_2O vertex. The average composition of the Grenville region would be less modified, if the paragneisses were in-

cluded, although there would be displacement towards the field occupied by the Abitibi rocks.

A tentative conclusion is that the averages of the Grenville and Abitibi rocks, particularly of the normative feldspars, are not far apart. It is probable that the properly weighted averages would show rocks about equally femic.

The belt with synkinematic albitic intrusive rocks lying south of Abitibi remains for consideration. The analyses of all rocks from Quebec, except some altered ultrabasic intrusive ones, are shown in Figure 4. The analyses, which include some of igneous rocks, are mostly of paragneiss, but can be supplemented by modes. For example, modes of plutonic rocks have been given by Wahl and the author (Wahl and Osborne, 1950), and thin sections are available from elsewhere along the zone. The data are too few to allow a definite conclusion, but they suggest that the average along this zone may be more albitic than that of Abitibi. Furthermore I have the impression from crossing the zone at several localities that, particularly on the west end, the average will be of a rock more salic than the averages for the Abitibi and the Grenville subprovinces.

There is fairly substantial evidence that the northeast striking structure of the transition zone cuts across the east-west strike of the Abitibi rocks and the north-south strike of the Grenville rocks. The albitic intrusives are related to this deformation. The stocks of Abitibi are probably satellitic intrusives of those of the transition zone, planes of weakness having allowed the emplacement of stocks of albitic rocks. The distribution of economic deposits in Abitibi suggests a geographic association with albitic rocks. Hence it is possible that ore deposits may occur on the Grenville side of the zone of synkinematic intrusives. The bulk of this zone is at present unmapped and but little prospected. The prevailing grade of metamorphism of all rocks on the Grenville side is higher than that in Abitibi, and hence it may be inferred that undiscovered mineral deposits have a different habit from those of Abitibi.

Use of Clays

It is obvious that, although the analyses of rocks from the Quebec Precambrian are more numerous than they were formerly, they are not yet numerous enough to enable a precise average composition to be computed. Many more analyses will be necessary. It is suggested that analyses of glacial clays and silts may be useful in arriving at an average composition. It would be particularly helpful to have analyses of such materials from places in the basin of glacial lakes Barlow and Ojibway and in the Laurentian region in localities not covered by the Champlain Sea.

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SECTION FOUR

Solenopora canadensis (Foord) and other Algae from the Ordovician of Canada

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ABSTRACT

The widely cited species *Solenopora compacta* (Billings) is probably a stromatoporoid, and not the alga it has been thought to be. Five species of *Solenopora* proper are recognized in the Canadian Ordovician: *S. canadensis* (Foord); *S. ouareauensis* Fritz; *S.* cf. *S. trentonensis* Brown; *S. canis*, n.sp. (Red River, Manitoba); and *S. dentata* (Chazy, Quebec). Two doubtful species of *Solenopora* are reviewed. Ami's *S. compacta minuta* is referred to *Girvanella* with doubt. A new species from the Whitehead formation of the Gaspé is described as *Petrophyton ? floreale.*

BEDS of limestone, often feet thick, have been described in the Ordovician of Scandinavia, Britain, North America, and the Baltic, which are made up of great numbers of subspherical masses of calcareous algae, usually referred to the genus *Solenopora*. Such beds have been reported on this continent as far south as Georgia, and as far west as Oklahoma, the algae usually being identified as *Solenopora compacta*. The same species has been recorded from various parts of northern Europe, in both the Ordovician and the Gotlandian.

Some of these records may be correct, but others may not, for there has been little agreement among authors as to the exact nature of the species. The usual text-book figures (for example, Shimer & Shrock, 1944, pl. 303, figs. 30–31) are taken from Winchell and Schuchert, who copied them from Nicholson (1888, p. 20, fig. 3), and they represent an Esthonian form, not an American one.

The present note attempts to place some of the Canadian species on a sufficiently firm footing to permit accurate comparison and specific discrimination. There is no attempt to go beyond simple description and naming, since Dr. J. Harlan Johnson of the Colorado School of Mines is engaged in studies of the morphology and systematics of the group.

The Nature of *Solenopora compacta*

Most American records of rock-building calcareous algae are of "*Solenopora compacta*," and other species have been defined in terms of their differences from this one. Fritz (1941, p. 157) and Wilson (1948, p. 14) have already pointed out that more than one species has been confused

under the same name, so that it is important to discover just what the typical form really is.

When Billings' original description (1862, p. 55) is studied, it seems clear that he was not describing the species with which the name has come to be associated. The original description, under the heading "*Stromatopora compacta* (N.sp.)," reads:

> This species forms small sub-globular masses, from 1 to 2 inches in diameter. The concentric lamellae are thin and closely packed together, there being in some specimens from 6 to 12 layers in the thickness of 2 lines [1.5 to 3 in one mm.]
>
> This species differs from *S. rugosa* in being much smaller and more compact. It occurs in localities where *S. rugosa* is not found, but at Paquette Rapids it is associated with that species in the same beds.
>
> *Locality and Formation.*—Island of Montreal and Paquette Rapids, on the Ottawa River. Black River limestone.
>
> *Collectors.*—Sir W. E. Logan, J. Richardson.

No figure was given in 1862, but the next year (in Logan 1863, p. 140, fig. 72) Billings figured *Stromatopora rugosa*; so we know what he meant by that name, and by inference, the general appearance of his *Stromatopora compacta*. Billings' type material cannot be found, and indirect evidence must be used to decide the nature of his specimens. The following points may be considered:

1. Although Billings' description was brief, it seems to apply better to a stromatoporoid than to an alga. There is no mention of radial structures, which one would expect in description of a *Solenopora*. *Stromatopora rugosa* is a *Stromatocerium*, and the identification of the Paquette Rapids material has been accepted by Galloway and St. Jean (1955, p. 7).

2. Two localities were given, at both of which the species was found in the Black River limestone. Material from Paquette Rapids was later described by Ami as *Solenopora paquettiana*, and the Montreal locality may be considered typical. According to Okulitch (1935, p. 103) and Clark (1952, p. 56) they did not find *Solenopora* in the Black River at Montreal, but they did find two forms of *Stromatocerium*: *S. rugosum* Hall and *S. canadense* cf. *minima* Parks.

3. In 1860 Dawson made a collection of fossils from the Trenton near Murray Bay and submitted it to Billings for determination. The most abundant and most conspicuous fossil in these beds is a large *Solenopora*, which makes up whole beds along the shore where Dawson collected, and it seems incredible that it would not appear in his collections. Billings (in Dawson, 1861, p. 143) listed *Stenopora fibrosa* (his usual name for a trepostome bryozoan) from these beds, but did not give this as a locality for his *Stromatopora compacta*, nor did he list this species in 1863 (in Logan, 1863, p. 163) in giving the Murray Bay fauna.

4. In 1883 Foord, in summarizing the bryozoans of the Trenton, did not include *Stromatopora compacta*, and in describing *Tetradium peachii*

canadense he did not mention Billings' species as being comparable. This omission is interesting, since Foord was assistant to J. F. Whiteaves, who suggested the study to him, and who must have approved it for publication. Whiteaves joined the Survey after Billings' death, but had previously been curator of the collections of the Montreal Natural History Society, at a time when the Survey offices were in Montreal. It must, I think, be assumed that Whiteaves was familiar with Billings' local species.

In summary: (1) Billings said his species was a stromatoporoid. (2) Stromatoporoids are found at the type locality, but *Solenopora* is not. (3) Billings did not recognize *Stromatopora compacta* in a collection which almost certainly contained *Solenopora*. (4) Whiteaves, who should have known *Stromatopora compacta*, did not consider it identical or comparable with *Tetradium canadense*.

Stromatopora compacta Billings is a Black River fossil. It may be an alga, but is more probably a stromatoporoid. If it is an alga, it cannot be identified from the original description, and no topotypical material has been found. There is no reason to think it is the common Trenton alga.

Dawson (1879, p. 53) seems to have been the first to suggest that Billings' species might not be a stromatoporoid. He compared it with a fine-tubed *Stenopora*, but wrote, "The species *Stromatopora compacta*, from the Trenton Limestone," thus suggesting that he was not dealing with Billings' Black River species, but with something else. Foord, after 1883, seems to have acepted Dawson's view and communicated it to Nicholson, who also accepted it (Nicholson and Etheridge, 1885, p. 530), and since then *Solenopora compacta* has been treated as an alga of the Trenton, but without further definition.

European Solenoporoids

Several species of *Solenopora* have been described from Ordovician of Europe, especially from the Girvan district of Scotland and from Esthonia. The genus itself continues into the Mesozoic. It may be that direct comparison of material would show the same species occurring on both sides of the Atlantic. Certainly, *S. lithothamnioides* (Brown, 1894, p. 148) seems very similar to *S. ouareauensis* Fritz. However, such comparisons must be left to those with access to more material. At present, comparison with Scottish species is made difficult by ambiguity concerning the first described and reputedly commonest form, *S. peachii*.

This species was first described, as *Tetradium peachii* (Nicholson and Etheridge, 1877, p. 166), from Upper Silurian pebbles in an Old Red Sandstone conglomerate at Habbies Howe, Midlothian. The description was brief, and the illustrations rather sketchy. Later, a *Solenopora* was found to be common in the Ordovician limestone at Craighead, near Girvan in Ayrshire (Nicholson and Etheridge, 1878, p. 31), and ever since the Girvan form has been described as *S. peachii* and has been regarded as

typical of the species. However, unless the original descriptions and figures are completely wrong, two species seem to be involved, and Lamont has recently accepted the Habbies Howe pebbles as being Gala, i.e. Early Gotlandian, in age (Lamont, 1947, p. 195). Certainly, material from these pebbles must be redescribed before the other Scottish species can be considered well established.

Fortunately, there is now no reason for confusion concerning the genotype, as Oepik and Thomson (1933) have recently described material from the typical locality (so far as material from the drift can have a typical locality) of *Solenopora spongioides*.

Canadian Solenoporoids

Specimens from the Canadian Ordovician which have been referred to *Solenopora* fall into four groups. First, there are five species which agree rather closely with the genotype. They have long cells which are regularly radial in position, so that a longitudinal section follows their length from top to bottom, and the whole has a strikingly fibrous appearance. The cells in cross-section are rather equal in size, but tend to vary strikingly in shape. "Septa" may be present in greater or less abundance.

Secondly, there are two species which (as Wilson has pointed out) differ strikingly both in longitudinal and in transverse section. The cells are irregularly disposed, so that any section cuts them in several attitudes, and no fibrous texture is seen. In cross-section smaller cells are seen to be interpolated between larger ones. The cell walls tend to be thick, and the cells themselves to have an outline more or less subcircular. There are no septa. I agree with Miss Wilson that these species cannot be *Solenopora* in any strict sense, but I do not think it would be helpful to propose another genus for them now. I leave them as ? *Solenopora*, as she did. The form described by Rothpletz (1908, pl. 3, figs. 1–6; 1913, pl. 1, figs. 5–6) from St. Joseph Island, Lake Huron, seems to be of this type and may be *S.* ? *paquettiana*.

Thirdly, the form described by Ami as *Solenopora compacta minuta* is referred below to *Girvanella* ? *minuta*. Finally, a species from the Whitehead formation, a "*Solenopora*" as the term has been used, is referred doubtfully to *Petrophyton*.

PLATE I (all stated magnifications are approximate)

Figures 1–4, *Solenopora canadensis* (Foord). (1) GSC 13306, a typical slab from the Lower Trenton between Cap à l'Aigle and Malbaie, Quebec, made up of masses of this species, X ½. (2) GSC 13307, Middle Trenton, east end of Cap à l'Aigle, a longitudinal section, showing the long parallel cells, X 7. (3) GSC 1561, transverse section of the lectotype, same locality as Fig. 1, X 25, showing the almost complete absence of septa and a group of smaller cells. (4) The same specimen, longitudinal section X 30.

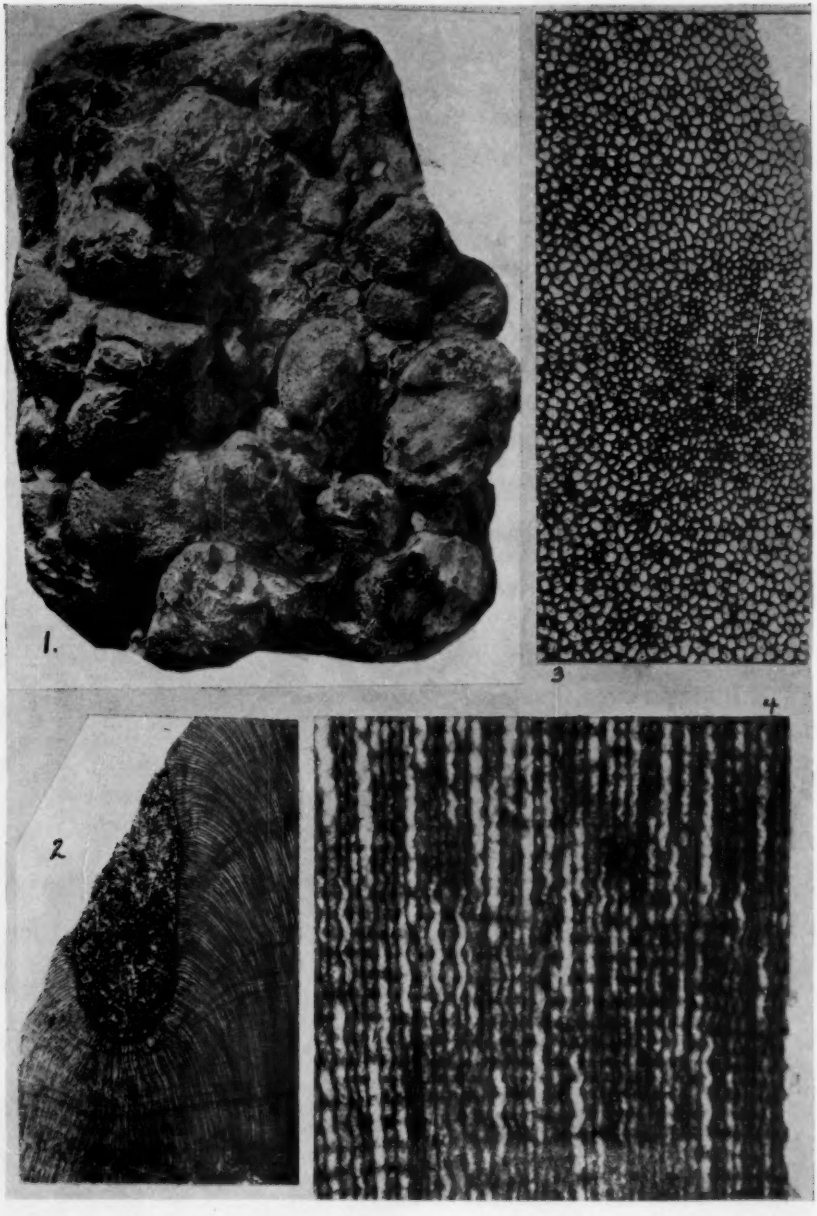

PLATE I

Description of Species

Genus *Solenopora* Dybowski, 1877

Genotype: *Solenopora spongioides* Dybowski, 1877 (see Dybowski, 1878, p. 124)

Solenopora canadensis (Foord, 1883)

Plate I; Figures 1–4

Tetradium Peachii var. *Canadense*. Foord, 1883, pp. 24–25, pl. VI, fig. 1

Solenopora compacta (Billings). Fritz, 1941, p. 157, pl. III, fig. 3

Foord used many specimens in drawing up his description of this species, and the collections of the Geological Survey of Canada contain eight specimens which must be considered as syntypes. They are:

(*a*) GSC 1561, and slides 1561a, 1561b. Murray Bay. J. W. Dawson, collector. Original of Foord's figure 1.

(*b*) GSC 1557, which has not been cut. Hull, Quebec. Foord, collector. Original of Foord's figure 1a.

(*c*) GSC 1559, 1559a and slide 1559b. Montmorency, Quebec. This could be the original of Foord's figures 1b–d.

(*d*) GSC 1558, and slide 1558b. Ottawa. T. C. Weston, collector.

(*e*) GSC 1558a, and slides 1558c, 1558d. Ottawa. T. C. Weston, collector. This is probably the original of Foord's figure 1e.

(*f*) GSC 7314 (slide only). Montreal. J. W. Dawson, collector. Original of figure 5, plate VI, of Wilson, 1948.

(*g*) GSC 13305 (slide only). Hull. H. M. Ami, collector.

There are some discrepancies in this list, as might be expected with such varied material collected over a period of time. Foord did not give either Ottawa or Montreal as a locality for his variety, and the status of the specimens from these places as syntypes might be questioned. However, as has been noted, it is probable that he did figure an Ottawa specimen. The point is of little importance, as a variety of forms were included under this name, and the original syntypes have only an historic interest.

I am choosing specimen 1561 as lectotype because (*a*) the specimen and two good sections are preserved, (*b*) the locality is known accurately, (*c*) abundant topotypical material is available for comparison or further studies, and (*d*) it is the form which Fritz treated as typifying *S. compacta* when she erected the new variety *ouareauensis*.

PLATE II (all stated magnifications are approximate)

Figures 1–2. *Petrophyton* ? *floreale* Sinclair. Holotype, GSC 13308, Whitehead formation, Grande Coupe, Percé, Quebec. (1) Transverse section, X 15, showing the elongate cells arranged in irregularly radiating groups. (2) Longitudinal section X 40, showing the short quadrate cells, and, at the right centre, a cell with the lateral expansion which shows as elongate in transverse section.

Figure 3. *Girvanella* ? *minuta* (Ami). Lectotype, GSC 13299, Quebec City formation, Côte d'Abraham, Quebec City, section X 25.

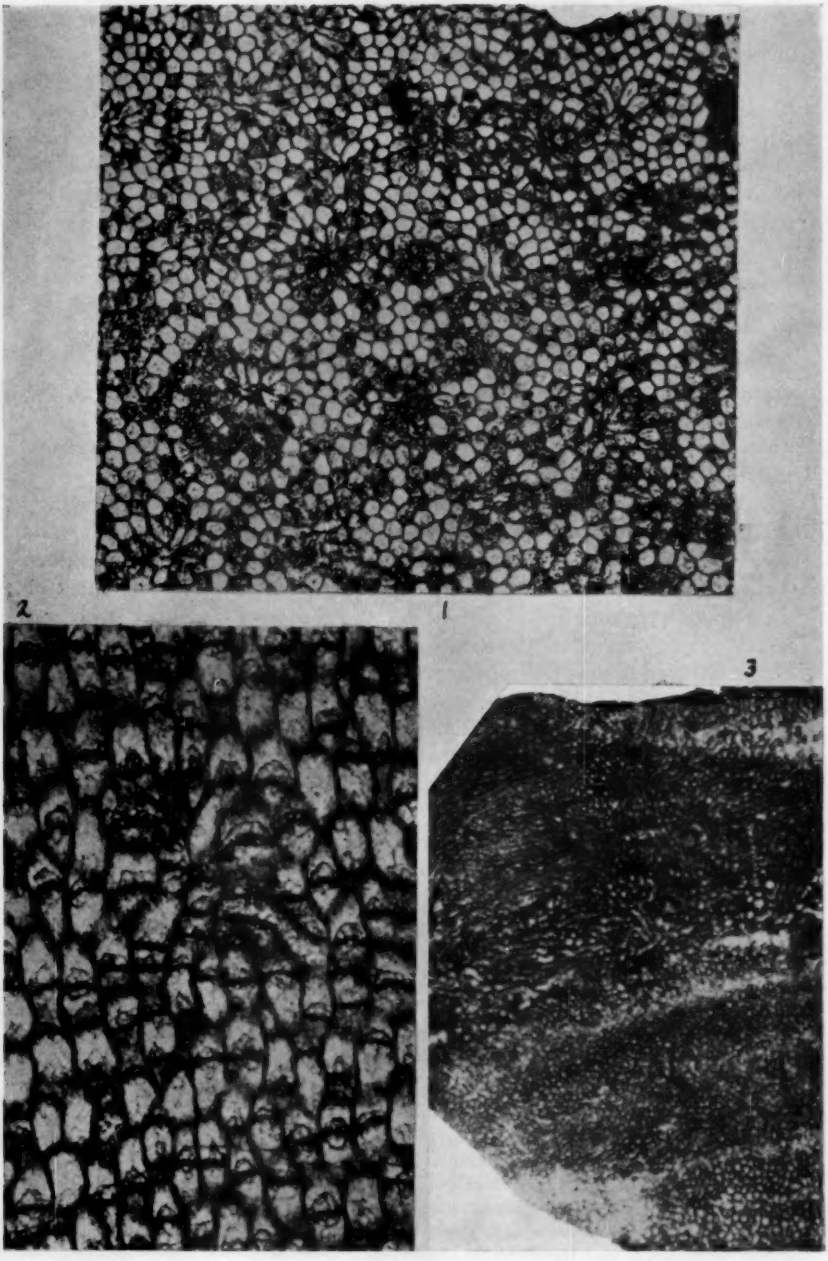

PLATE II

Lectotype: GSC 1561, and slides 1561a, 1561b.

Type locality: Cliff between Malbaie and Cap à l'Aigle, Quebec. The stated locality, "Murray Bay," refers to the district as a whole, but Dawson's paper (1861) make it clear that the precise locality is the cliff he calls "l'Ecorché." It is tempting to think that this specimen might have been one of those sent by Dawson to Billings in 1860, but it bears no date and might have been collected on a later, unrecorded visit to Murray Bay.

Type horizon: Lower Trenton.

Distribution: This species seems to be widespread and, indeed, is probably the form often referred to in lists where "*S. compacta*" is cited. But this cannot be verified without examination of more material. Near Murray Bay it is abundant at the type locality, and also in the same beds exposed along the shore east of the town wharf in Cap à l'Aigle. It also occurs commonly in slightly higher beds (with *Cryptolithus*) in a small quarry below the Presbyterian chapel in the east end of the village, from which specimen 13307 was collected.

Description: The lectotype is a rounded mass about 70 mm. across, which is about the average size in these beds. In longitudinal section the cell walls are regularly crenulate; there are no tabulae; the cell walls are rather regularly nodose, being thickened about every 0.14 mm. The alignment of these nodes from wall to wall gives rise to the illusion of transverse structures which do not exist. Consideration of the origin of these nodes is tempting, but would lead too far from the purpose of the present notes.

In cross-section the cells are polygonal, and similar in size in any one region, but areas of distinctly smaller cells occur here and there. Miss Fritz has already called attention to these areas, comparing them in appearance to the maculae of bryozoans. This is a very different arrangement from that seen in the questioned species of *Solenopora* described below, in which the smaller cells are placed between the larger. In this species all the cells of a given area are of the same size, large or small. The cell walls are comparatively thick, and septa are almost completely absent.

Solenopora dentata, new species
Plate III; Figures 1–3

Holotype: GSC 13302 and slides 13302a, 13302b. Paratypes: GSC 13303, 13304. Sinclair coll. et don.

Type locality: Village Bélanger, Ile Jésus, Quebec.

PLATE III (all stated magnifications are approximate)

FIGURES 1–3. *Solenopora dentata* Sinclair. Laval formation, Village Bélanger, Quebec. (1–2) Holotype, GSC 13302, longitudinal and transverse sections X 25, the longitudinal section showing well the strong resemblance to *S. ouareauensis*. (3) A paratype, GSC 13304, X 1, showing one of the common forms of the species.

FIGURES 4–5. *Solenopora* cf. *S. trentonensis* Brown. Cobourg beds, Ottawa. GSC 13309, longitudinal and transverse sections X 25.

FIGURE 6. *Solenopora* ? *paquettiana* Ami. Lectotype, GSC 9315, Basal Trenton beds, Paquette Rapids, Ottawa River, X 7.

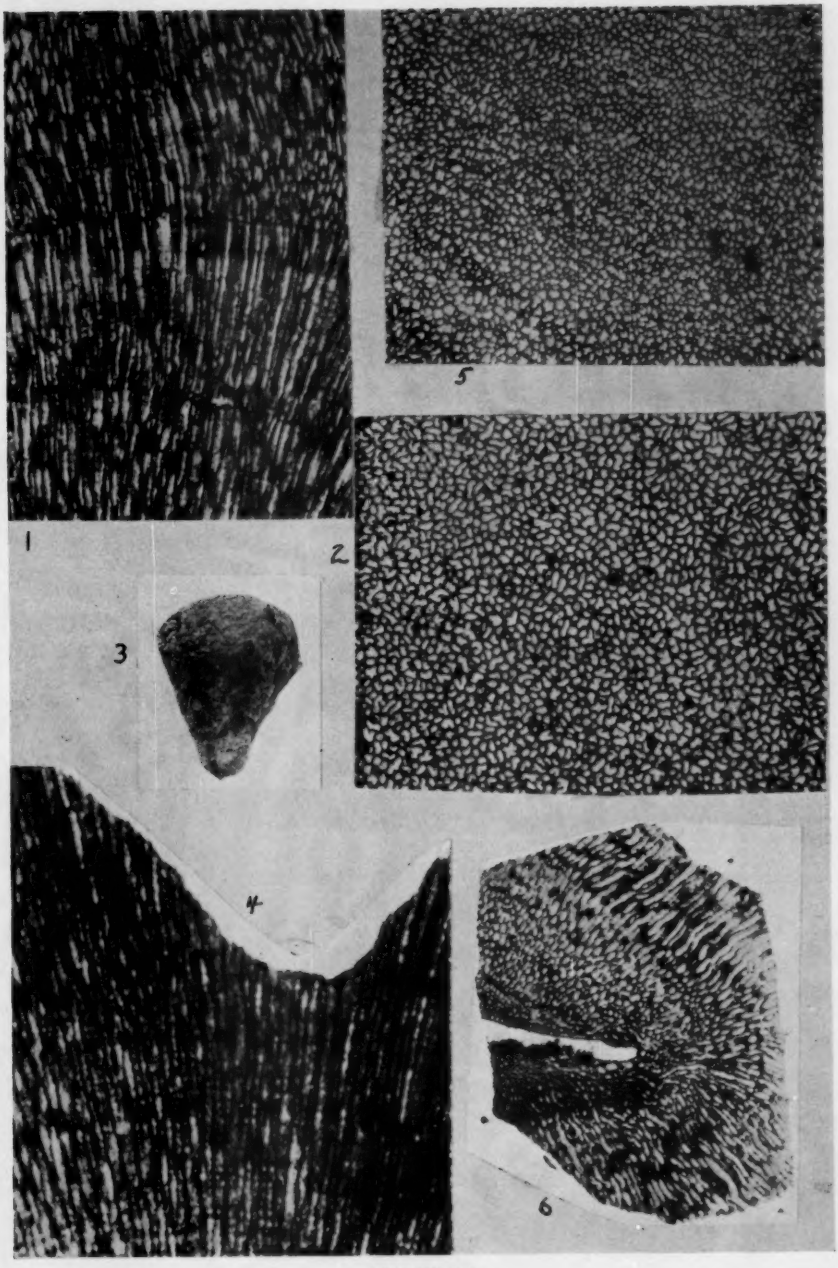

PLATE III

Type horizon: Upper Chazyan, Laval formation.

Some beds of the Laval formation on Ile Jésus are made up of great numbers of these organisms. Many are subglobular, some are irregularly cerebriform (e.g., 13303), but many are rather regularly pyriform (see Plate III, Figure 3), a shape which I have not met in other *Solenopora*. While it would be impossible to say that all of the thousands of specimens in these beds are of one species, those selected for sectioning were identical internally, although they differed greatly in over-all shape. *Solenopora compacta* has been reported to be abundant in the Upper Chazy on Lake Champlain, but in noting this occurrence Seely (1910, p. 274) gave no description and only repeated figures copied from Foord, so that it is not possible to say from the literature how the Vermont material compares with that now described from Montreal.

The various species of *Streptochetus* described by Seely (1902, p. 156 et seq.), which are superficially similar to *Solenopora*, were all collected from lower beds in the Chazy. Without extensive sampling it cannot be said that they do not occur in the Montreal district, but I have not recognized them. Clark (1952, p. 46) has recorded a *Girvanella* sp. from the Laval formation, which would indicate something akin to Seely's fossils. Some of Seely's species, for example, *Streptochetus brainerdi* (1902, pl. LVIII, fig. 8), seem to be consortia of a *Girvanella*-like organism with one more like *Solenopora*, and recall associations described by Wood (1941, 1948).

Description: Most examples of this species are between 30 and 50 mm. in diameter. In longitudinal section the cell walls are seen to be essentially straight or only irregularly crenulate; no nodes were seen, and no tabulae. There are about 18 cells in a width of one mm.

In transverse section the cells appear highly irregular in shape, their length being usually about twice the width. Some cells have as many as four septa, some have none, but many have a single septum rising like a sharp tooth from the middle of one side. Although the shape of the cells is so irregular, their size is rather constant. The walls are rather thick for the size of the cell.

This species is most similar to *S. ouareauensis* Fritz, but the cells as seen in transverse section are elongate rather than equidimensional.

Solenopora ouareauensis Fritz, 1941

Solenopora compacta ouareauensis. Fritz, 1941, pp. 158–159, pl. III, figs. 1–2.

Cotypes: Royal Ontario Museum of Palaeontology, 23356.

Type locality: Near Joliette, Quebec, on the Lac Ouareau River.

Type horizon: Black River. Dr. Fritz has very kindly informed me that the precise horizon is bed number 5 of Parks (1931, p. 21).

This species has been well described, and nothing is needed here except notice of it as a valid species. It seems to be rather common in the Black River and early Trenton.

Solenopora cf. *S. trentonensis* Brown, 1894

Plate III; Figures 4–5

cf. *Solenopora compacta Trentonensis*. Brown, 1894, p. 147, fig. 2

Solenopora compacta. Wilson, 1948, pp. 14–15 e.p., pl. VI, fig. 6

not *Actinostroma trentonensis* Weller, 1903, p. 139, pl. VI, fig. 8; pl. VII, fig. 3–4.

Hypotype: GSC 13309. Sinclair coll. et don.

Locality: Corner of Carling Avenue and Booth Street, Ottawa.

Horizon: Cobourg.

Brown gave no formal description for his variety, and no locality other than North America. Until the type material is redescribed the variety cannot be identified with certainty. Brown's specimen was in Nicholson's collection, and its present location is not known to me. It might be the same as the specimen figured by Nicholson and Etheridge (1885, pl. XIII, figs. 4–5) from the Trenton [Cobourg] of Prince Edward County, Ontario, although the figures do not agree. However, in each case only a small portion of a slide was drawn, and they may be the same.

There is no strong similarity between the present specimen and Brown's illustrated cross-section, but under the circumstances no name is proposed for this Cobourg species. It is described here because it is one of the forms figured by Wilson. Only the one slide is present. It was apparently cut from a somewhat elongate specimen about 25 mm. high. In longitudinal section the walls are seen to be faintly and irregularly crenulate; they are not nodose. There are no tabulae, but the growth of the whole was interrupted at intervals of about one mm., with resumption of growth with new cells. There are about 22 cells in a width of one mm. In transverse section the cells are rather uniform in size, but irregular in shape; there are numerous septa; the walls are rather thin.

This form is very similar to *S. ouareauensis*, from which only the slightly smaller cells distinguish it, if indeed it can be distinguished.

Solenopora canis, new species

Plate IV; Figures 1–3

Solenopora compacta, Billings (Sp.). Whiteaves 1897, pp. 237–8

Holotype: GSC 7128, and slides 7128a, 7128b. T. C. Weston, collector and lapidary, 1884.

Type locality: Washow Bay, Lake Winnipeg, Manitoba.

Type horizon: Red River formation, Dog Head member.

Description: The type specimen is a subspherical mass about 35 mm. in diameter. The longitudinal section shows long cells, their walls not quite straight, but with no regular crenulations. Here and there the walls are thickened, but not in such a manner as to produce regular nodes. No tabulae are seen. Throughout this slide, and, so far as can be seen, throughout the whole specimen, lacunae about 0.5 mm. in diameter are common.

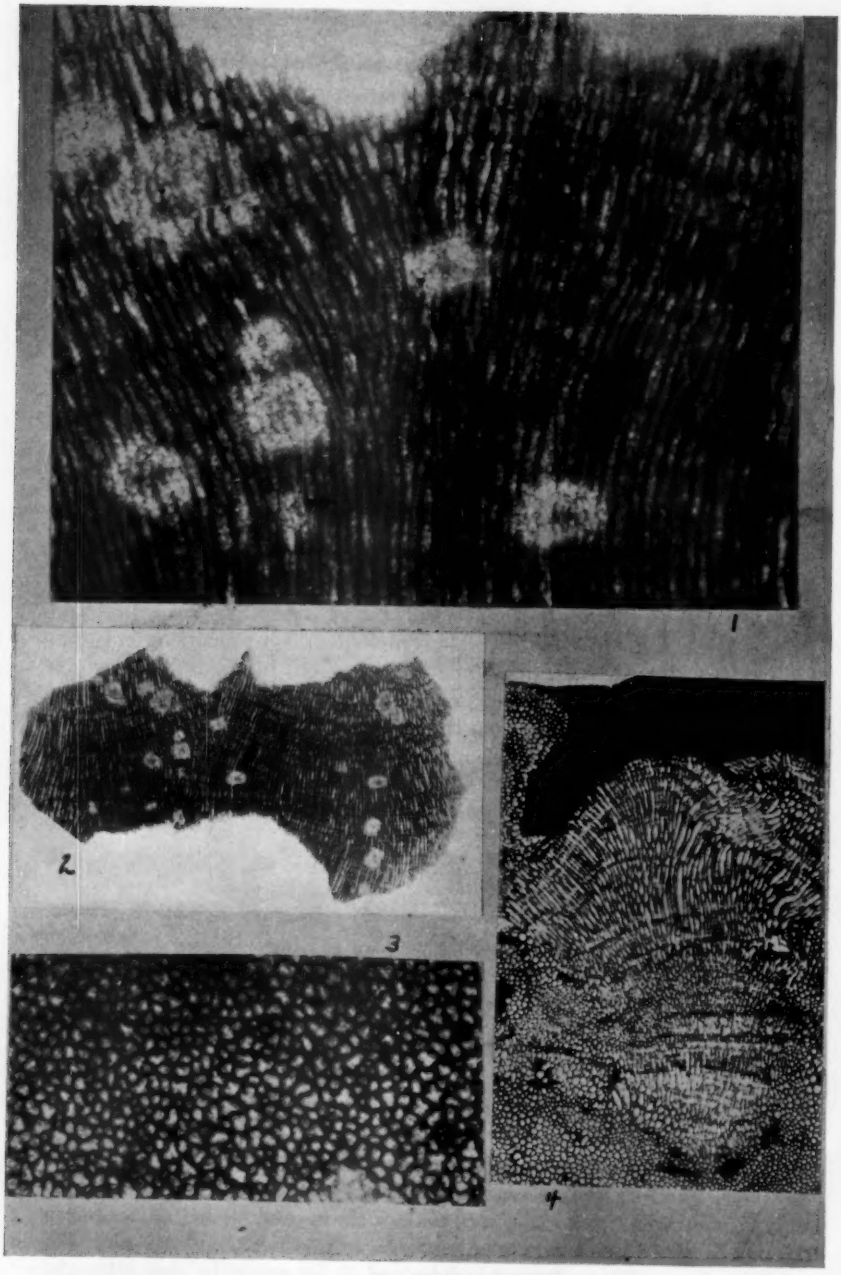

PLATE IV

They are clearly due to resorption of the cell wall after its formation, and agree well with the type of sporangium suggested by Wood (1944, p. 112). Again, it would be inappropriate to pursue their significance farther.

In transverse section the cells are equidimensional and show no striking differences in size. The walls are comparatively thick; septa are numerous and usually short and stout. There are about 16 cells in a width of one mm.

This species resembles *S. ouareauensis*, but lacks the regular interruptions of growth which seem to characterize that form. Until the nature of the "sporangia" is better understood no importance can be attached to them, striking though they be.

Solenopora ? *paquettiana* Ami, 1892

Plate III; Figure 6

Solenopora Paquettiana. Ami, 1892, p. 98

Solenopora paquettiana. Fritz, 1941, p. 158

Solenopora ? *paquettiana*. Wilson, 1948, p. 15, pl. VI, figs. 1–2

This species has been well described by Wilson, and I wish only to record the nature of the type material.

The Survey collections contain six slides (no specimens seem to be extant) labelled *Solenopora Paquettiana* N. sp., all from Paquette Rapids. They were all made by Weston and numbered in his register of slides: 883, 884, 825, 826, 916, 917. They were made at three different times and probably from three specimens, although that is not now determinable. Two of these syntypes have been figured by Wilson and given type numbers. The others are now numbered, and the syntypes are:

Slide number	Type number
883	9315
884	9315b
825	9315c
826	9315d
916	9315e
917	9315a

Since more than one specimen is represented here, No. 9315 is designated as lectotype. It is the slide figured by Wilson as figure 2. Slide 9315b is thought to have been cut from the same specimen. The lectotype had apparently grown on some object (a brachiopod shell ?) which has since disappeared.

PLATE IV (all stated magnifications are approximate)

FIGURES 1–3. *Solenopora canis* Sinclair. Dog Head member of Red River formation, Lake Winnipeg. GSC 7128, Holotype. (1–2) Longitudinal section X 35 and X 7, showing the resorbed lacunae. (3) Transverse section X 30.

FIGURE 4. *Solenopora* ? *embrunensis* Wilson. GSC 13301, a specimen from the type locality, Lowville formation, near Embrun, Ontario, a section X 7.

In longitudinal section the cells are seen to be irregular in growth, with their walls frequently wavy but forming no regular pattern of crenulations. No regular thickening of the walls is seen nor any tabulae.

In transverse section the walls are frequently thick and the cells correspondingly subcircular. Small cells are frequently seen between larger ones. No septa are seen. In places the specimen has been imperfectly silicified, so that the walls are not complete, but this appears to be accidental and not analagous to septa formation.

Solenopora ? embrunensis Wilson, 1948

Plate IV; Figure 4

Solenopora ? embrunensis Wilson, 1948, pp. 15–16, pl. VI, figs. 3–4

Holotype: GSC 13300. Hypotype, GSC 13301. Sinclair coll. et don.

Type locality: Embrun, Ontario. A small quarry along the New York Central tracks, just southwest of the village.

Type horizon: Lowville limestone.

This species has been adequately described and is noted here mainly to remove the ambiguity concerning its age. Solenoporoids do occur in the Hull at Embrun, but they seem to be true *Solenopora*, probably *S. ouareauensis*.

S. ? embrunensis forms small masses, usually about 40 mm. across. The surface is often cerebriform, and a depressed discoid shape, flat on top, is common.

Genus *Girvanella* Nicholson and Etheridge, 1878

Genotype: *Girvanella problematica* N. & E. (1878, p. 23)

Girvanella ? minuta (Ami, 1892)

Plate II; Figure 3

Solenopora compacta var. *minuta*. Ami, 1886, p. 116 (nude);
Ami, 1892, pp. 97–9

Syntypes: GSC 13299 and 13299a. No specimens seem to be extant, and only these two slides remain. That here numbered 13299 is designated as lectotype. H. M. Ami and N. J. Giroux, collectors.

Type locality: Côte d'Abraham, Quebec City.

Type horizon: Quebec City formation.

This species is not very satisfactory, but it might be useful to put on record what the name refers to. The specimens seem to have consisted of small masses of unknown shape, about 3 mm. thick. Somewhat over half this thickness (in the lectotype) is made up of tubes running parallel to the lower surface, so that only their ends are seen in the longitudinal sections. Within this zone a rough banding is seen, owing to destruction or imperfect preservation of some of the cell walls. The cells, or tubes, in the outer zones are seen lengthwise, and thus were directed mainly towards the surface and at right angles to those in the lower part of the specimen. They are not

highly contorted, but are very irregular and frequently recurved in rather gentle arcs. They are about 0.04 mm. in diameter. In cross-section the tubes seem to have been almost circular. No septa or other structures have been seen in them.

Genus *Petrophyton* Yabe, 1912
Genotype: *Petrophyton miyakoense* Yabe, 1912 (p. 6)

Petrophyton ? *floreale*, new species
Plate II; Figures 1–2

Holotype: GSC 13308, and slides 13308a, 13308b. Sinclair coll.
Type locality: Grande Coupe, Percé, Quebec.
Type horizon: Whitehead formation.

The holotype forms an irregularly cubical mass about 50 mm. across. In longitudinal section the cells are quadrate or sometimes elongate and flask-shaped. Tabulae are transverse or a little convex and seem to be somewhat thicker than the walls. Cells are about 0.25 mm. long, about 0.11 mm. wide.

In transverse section the cells are polygonal, rather uniform in size. The walls are usually thick, but this thickness varies from place to place. There are no septa. In places groups of elongate cells are seen, their length about twice their width, usually roughly radial in arrangement. Wood was sceptical of the stellate groups of cells described by Brown in *Solenopora jurassica* and pointed out the tendency for the eye to see patterns in random arrangements, and the fact that these stellate patches had not been seen in longitudinal section. In the present species it is clear that the cells which appear elongate in transverse section are also seen in longitudinal section, as the L-shaped cell in the figured slide. Thus the elongate cells have a three-dimensional reality.

The generic relations of this species are not clear to me. I place it questionably in *Petrophyton* because of its similarity to the species described by Høeg (1932, p. 82) as *P. Kiaeri*, but neither the Norwegian nor the Canadian species agrees closely with Yabe's generic description. Brown's *Solenopora jurassica*, which is in some ways similar, was taken as type of a new genus *Solenoporella* by Rothpletz (1908, p. 10), but I am not sure how this form is to be distinguished from *Pseudochaetetes*. However, I must leave to workers more familiar with these Mesozoic plants the task of properly assigning the species.

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Note Added in Proof, March 11, 1957

In describing the Ordovician faunas of Newfoundland, Billings (1865, Pal. Foss. vol. I, p. 212) notes that he had a specimen from Division L at Point Rich which was "not distinguishable from" *Stromatopora compacta*.

This specimen has now been found, numbered 537 in the collections of the Geological Survey. It is clearly a stromatoporoid. This specimen is not a type, but it supports the suggestion made above on logical grounds, that Billings' species was not a *Solenopora*.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
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SECTION FOUR

The Problem of Finding More Geologists

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ABSTRACT

The need for more geologists and geological engineers who may assist in the development of Canada is becoming increasingly evident. The author suggests that neither salaries nor working conditions are at the root of this problem. Our young people in that period of their life when they are thinking of choosing a career should be given an opportunity to learn of the satisfying and challenging career which geology has to offer them. This opportunity should be presented during high school days. By the time a student has reached a university he may already have decided on a career.

Introduction

MARK Twain once wrote: "Everybody talks about the weather, but nobody ever does anything about it." This complaint might equally well be made about the quantity and quality of those graduating in mining and geological engineering. Today one has only to read any technical journal for a comparatively short time to learn that in Canada, as in Great Britain and the United States, there is a shortage of high grade engineers and scientists. Furthermore, it would seem that the worst is yet to come. Not only are men, and women, entering into the sciences in inadequate numbers but also there are many educationalists who feel that those who are entering do not represent that share of the best brains which must enter these fields if Western civilization is to survive the onslaught of totalitarianism. Each writer in turn offers one or more explanations for our increasing dilemma. However, if the reasons given in this paper are valid, then Fellows of the Royal Society have it in their power to improve the situation, and this applies particularly to those Fellows connected directly or indirectly with education.

In his opening remarks to the Society in 1946, Dr. E. S. Moore, our President that year, said that "we must review from time to time the possibility of making the Society a more potent influence in this country." It is because of my belief that we, as Fellows of the Royal Society, have a wonderful opportunity of making a useful contribution to our country and our profession that I present this paper.

The Problem

In a broad way young people choose their careers on the basis of either their natural aptitudes and likings or the tangible or intangible returns which they hope to win from their chosen calling, or more probably combinations of all three. Those young people who want to enter a profession

are more apt to be of high calibre than those who just drift into some field of endeavour for lack of anything better to do. Thus it seems pertinent to inquire as to the time at which careers are decided upon by young people. Colonel McLean, to whom as many students as possible at the University of British Columbia are directed for aptitude tests and counselling, was questioned on this matter. Although stating that it would be difficult to provide definite statistics Colonel McLean was inclined to think that possibly as many as 70 per cent of those entering university had a general idea of the course they intended to follow: at least that percentage knew what they did not like or what held no attraction for them. As far as geology and mining engineering are concerned, university pre-engineering courses contain little to attract a student into these fields. English, mathematics, chemistry, physics, social science and a language, vital though they all are, do nothing to suggest the challenges or opportunities that await potential students in what we may, for convenience, term the Earth sciences. Thus it would appear that in the majority of cases a career is being more or less decided upon when the pupil is in high school. When it is realized that only a small percentage of high school students ever reach university, then it becomes clear that for any long-term remedy for our present lack of engineers and scientists, we must look to our homes or schools. It follows, therefore, that we must try to determine the factors which influence high school students in the choice of their careers. I propose to deal first with the non-financial and then with the financial aspects of the problem.

Factors Influencing the Choice of a Career

Non-Financial

Experience is one of the most difficult things to pass on from one generation to another. Although there is a wealth of advice available to those who seek it, through the media of books or of people, everyday associates and associations, coupled with personal experience, determine most of the major decisions of life. "What the old cock crows, the young ones learn" is an adage with much truth in it. In Canada today we have more and more people living in cities where children learn of the world and its tasks from their parents, the friends of their parents, movies, television, newspapers, and a barrage of advertising which, in one form or another, bombards them from the time they awake until they fall asleep. Aldous Huxley in *Brave New World* showed all too vividly what could possibly result from an all-pervading subconscious education by propaganda.

Professor F. A. Forward put some valuable material before the Gordon Commission on Canada's Economic Prospects. Among the many interesting facts he submitted, one was particularly pertinent to this discussion. Of 105 engineering students in third and fourth year Geology, Mining and Metallurgy, in attendance at the University of British Columbia, only 5 came from the metropolitan areas of Vancouver and Victoria, unless they came

from families which had some close connection with the mining industry. In other words, except for children who have personal contacts with people engaged in mining, only those from our smaller communities would appear to have a reasonable opportunity for realizing just what the mining industry offers to Canada, both as a vital contributor to our national wealth and as a challenge to potential students of the Earth sciences. Indeed, in British Columbia, where we have a government peculiarly attuned to public desires, we find that it gladly provides a grant of $20,000 for professional entertainment in contrast to a modest $5,000 to the B.C. and Yukon Chamber of Mines. When it is realized that at the University of British Columbia between 55 and 60 per cent of the students come from the metropolitan areas of Vancouver, Victoria, and New Westminster, then the seriousness of the problem becomes readily apparent. It would be my opinion, based on numerous discussions with geologists from many parts of Canada, that similar results would be obtained from studies made elsewhere. Children are great imitators: they are natural hero worshippers. In our cities, who are offered as potential heroes? Not geologists and mining engineers, who receive little publicity either in the deluge of daily propaganda to which children and adults alike are subjected or from the adults whom children encounter or have held up to them as examples during their formative years. Business opportunities are paraded by chambers of commerce together with much ado about the need for recruiting a continuing supply of alert young men and women. Doctors, lawyers, and bank managers have been glamourized in film and novel, and by direct contact with most families such men have many opportunities for stimulating the interest of young people in their profession. Scientific achievements—the atomic and hydrogen bombs, new fabrics, guided missiles, radio, and television—and the great engineering feats of Kitimat, Boulder Dam, the Quebec and Lion's Gate bridges, the St. Lawrence Seaway, and great gas and oil pipe lines, all these are seen and talked about so constantly that only the most unimaginative could fail to glimpse the challenge, and the financial rewards, offered in chemical, civil, electrical, mechanical engineering and the related fields.

Thus, in the natural course of events there will be adequate recruitment for many professions. However, such is not the case for the Earth sciences. The fact remains that we are not getting either in quantity or in quality the men and women we need for the full development in Canada of those professions dependent on training in the Earth sciences. The Geological Survey of Canada at one time this year had less than 20 suitable candidates for some 70 vacancies for geological assistants. The University of British Columbia Placement Officer had from three to four job opportunities for every geological graduate. Similar situations are reported elsewhere in Canada. Fortunately, one relatively easy solution to our problem is available, a solution which the author has advocated, without success, in British Columbia. If a system is failing, be it in sport, politics, or domestic life, a

change is indicated. If home and society generally offer no solution to this problem, then surely it is to our schools and universities that we must look for an answer.

Having come to this conclusion some years ago I examined some of the "General Science" courses given in the schools of British Columbia. Three texts, *Mastering our Environment, Science and Life,* and *Science and Progress,* formed the basis for an uncritical but general appraisal. It would be most helpful if more of us were familiar with these books: they comprise a wealth of information; they are well edited; and they have within their covers enough background material to stimulate any amount of interest in virtually any walk of life, including geology and mine finding. The question I then asked myself was why with all this good material available we were not obtaining the results that we might reasonably have anticipated? After teaching several geography courses to teachers at summer school sessions of the University of British Columbia the following observations would seem to be pertinent. In spite of the wealth of information on minerals, rocks, and such practical tools as the gold pan, only a negligible portion of the men and women assigned to teach these fascinating aspects of geography had ever studied them seriously, much less applied any knowledge that they might have acquired in any practical way. Many teachers have never studied minerals with any mineral collection or even used a set of crystal models. Museums are most useful in sparking the interest of children in various matters. Even small collections of minerals, rocks, and samples of ore can be most useful, but many schools lack even these. The author had one class of seventy-five students, largely teachers, and only about half a dozen had any practical ideas on how to use a gold pan and only one—a war veteran who had lost one hand—was able to assist in demonstrating just how easy and how much fun panning can be. Anybody who has taught small boys how to pan will agree that it is a simple operation, provides a constant delight to the learner and, furthermore, costs negligible amounts in comparison with the elaborate equipment found in many of our schools. Minerals may not stimulate everybody, but they are natural items of interest to many small boys. It has been my experience that there are few areas in British Columbia that do not possess their share of small boys, and older boys also, who at one time or other did not possess a collection of "rocks" about which they were curious and speculated as to their origin. Samples sent into our university for identification actually constitute a serious nuisance and testify both to a natural interest in geology and to the present inability of many of our science teachers to cope with these questions, which they could easily answer had their university training given them any practical background in this field. Doubtless many other parallel examples will occur to readers.

The preceding suggests that those of us who have some connection with education should do something to provide teachers who can in turn do something to interest youngsters in the Earth sciences. Perhaps it would be well to find if this idea would fit in with the aims and objectives of those

who direct education in our secondary schools. Fortunately the answer to this question is easy to find. In the Preface to *Mastering our Environment* we find the following statements which seem decidedly pertinent:

> It [the book] provides learning experiences for all who are interested in intelligent exploitation and conservation of our natural resources.
>
> The content of the course shall bear direct significance to life's problems and activities. . . . The learning activities shall be of such a nature that pupils may be interested in undertaking them and in carrying them to completion under the motivation and helpful guidance of a well trained teacher. . . . Some activities, at least, shall be of such a nature that they may be organized into problems identical with the problems of life.

Elementary geology, mineralogy, and geochemistry not only are thrilling experiences for children when they are well taught, but also provide a useful way of showing how the sciences of geology, agriculture, and chemistry are related to each other and to human health.

With all the above thoughts in mind a start was made at the University of British Columbia by putting on a course in geography which would have provided, in the fullness of time, the teachers necessary for the execution of the plan suggested in this article. Results were just beginning to be obvious, teachers were telling of their success in interesting their students in rocks and minerals, when the course was discontinued. It was claimed that so few teachers, or more correctly, potential teachers, were taking the course, that the time being allotted to rocks and minerals was not justified, since other more vital aspects of geography would thereby be neglected. This may well be true and yet it seems hard to reconcile with the fact that last year more than 450 men and women, including at least one high school principal, subscribed time and money to attend night classes at which the instructors were some of the very people who would have been involved in teaching minerals and rocks to geographers.

As has been stated earlier, youngsters are great hero worshippers. During the 1954 Empire Games, Bannister and Landy inspired many of our young people just as Burleigh, Lowe, Williams, Zatopek, and Nurmi had done before. Canada has in the stories of her mine finders many a romance which, if told with knowledge and enthusiasm, would do much to stimulate the study of geology, mining, and metallurgy. After all why shouldn't the stories of Sullivan, Horne, Hollinger, Camsell, Dawson, LaBine, Barker, Joubin, Gray, Rivrin, and many others be told? They have done much more for Canada than many of those whose names are today continually flaunted before our young people. Emulation of these men could well instigate interest in one of the Earth sciences and do much to remedy a situation which so many deplore and about which we seem to be doing so little.

Financial

It is probably correct to assume that nobody should ever choose a career solely on the basis of obvious financial returns. Nevertheless comparative financial returns are bound to have some influence on a young man: after all, nobody can help seeing that some obtain more for their efforts than

others. In the last fifty years the relative incomes received from various occupations have varied more than most men realize. Consider a cook on the one hand and a young geological engineer with a newly acquired Ph.D. on the other. In the first decade of this century it would not have been out of the way for the cook to get, say, $25 a month and all found; the budding engineer might well have expected to get at least $125 a month, if he were working for the government, or as much as $200 a month and all found if he were to start in with a mining company, assuming that he had picked up some experience while he was still an undergraduate. In other words, an engineer might have received from five to eight times the remuneration of a cook. Comparisons are odious but, if this ratio were to be adhered to today, when cooks readily get from $250 to $325 a month and all found, our Ph.D. should be commanding the munificent sum of from $1,250 to $2,600 a month and all found. Furthermore, fifty years ago income taxes were not the problem they are today. Nobody would argue that these staggering figures either could or should be paid. At the same time nobody is likely to claim that the changes which have taken place in the relative emoluments of these contrasting professions do not partially explain why today we are faced with a comparative shortage of high grade applicants for our degrees in geological and mining engineering. Nearly every university professor can point to engineering students who have from necessity chosen to work as labourers or packers rather than as technical assistants during their academic vacation: financial necessity overruled their normal desires. Similarly a few decades ago many budding young doctors and lawyers worked as assistants in various operations connected with the technical side of mining or forestry. Today I would hazard a guess that only boys with financial backing from their families can do this; most flock to the relatively better paid jobs such as there are at Kitimat or on pipe line construction. It would surely seem that some changes are needed in the relative returns obtainable from various occupations, that is if we wish to get men of higher calibre into the field of Earth sciences.

Conclusions

In our world of today young people in their formative, career-choosing years are exposed more and more to the possibilities inherent in business and in most professions, but less and less to the opportunities available in the Earth sciences. Our schools provide the machinery whereby the Earth sciences can be taught but, in general, our universities, in their schools of education, do not provide for the training of teachers in those aspects of the Earth sciences, the rudiments of which are essential if children are to be inspired by the challenge that the Earth sciences have to offer them.

Some changes in emoluments relative to those provided by competing professions would help to establish the prestige of the Earth sciences and this in turn would eventually aid recruitment.

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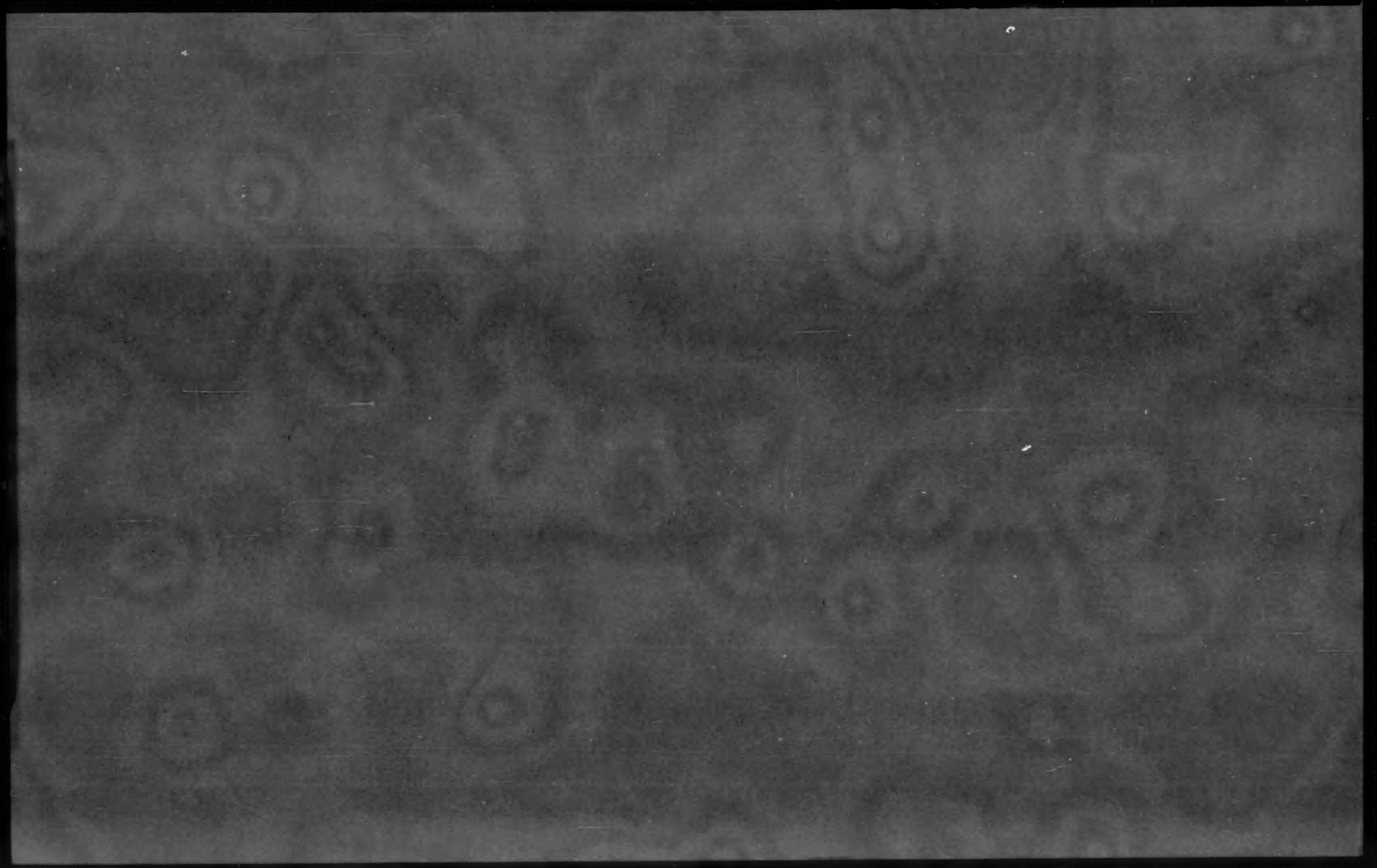
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